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Volume 26 MARCH, 1956 Number 1

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the Journal are the following:

Grain-size analysis of Jacksonian sediments of Mississippi and adjacent areas. By Ming-Shan Sun.

Origin of calcareous ooliths. By P. H. *Monaghan and Melba L.* Lytle.

Clay minerals from the Röt member of the Triassic near Göttingen (Germany). By Friedrich Lippmann.

Soil boulders in the Temecula arkose. By John F. Mann, Jr.

Lower limits of the *So* coefficient. By William F. Tanner.

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An application of the theory of sediment transport by turbidity currents to the dredging of navigable channels. *By John S. Bradley.*

Estimation of Recent sediment size parameters from a triangular diagram. *By William J. Plumley and Donald H. Davis.*

Organic sedimentation in Warnbro Sound, Western Australia. By Maurice A. Carrigy.

Methods and preliminary results in a study of minerals from the eastern Gulf of Mexico. By Nora G. Fairbank.

Multivariate analysis of mineralogic, lithologic, and chemical composition of rock bodies. By W. C. Krumbein and John W. Tukey.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 1, PP. 3–14
FIGS. 1–8, MARCH, 1956

PETROLOGY OF THE ARENACEOUS BEDS IN THE CONOCOCHEAGUE FORMATION (LATE CAMBRIAN) IN THE NORTHERN APPALACHIAN VALLEY OF VIRGINIA

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ABSTRACT

This paper is concerned with the petrology and stratigraphy of the arenaceous beds of the Late Cambrian Conococheague formation in the northern Appalachian area of Virginia. The arenaceous beds are confined to two definite stratigraphic positions in the formation. The Big Spring Station member occurs at or near the base of the formation and a higher succession of arenaceous beds are near the top. Both sandy phases are laterally persistent throughout the area in the western and medial parts of the Appalachian Valley but only one thin phase is present on the easternmost edge of the Valley.

The arenaceous beds are calcareous sandstones and orthoquartzites which are cemented with calcium carbonate or silica. The dominant constituent is quartz which is moderately well-rounded and sorted. The principal heavy minerals are well-rounded tourmaline and zircon and local floods of other minerals such as hornblende and topaz. Angular overgrowths on the tourmaline indicate such growths have developed in place, whereas abraded overgrowths denote sedimentary reworking of some material. Relatively angular and unstable minerals associated with very stable varieties suggests two distinct suites of minerals derived from different sources.

In nearly every sample the quartz of the calcareous sandstones has been replaced around the edges by the calcite cement, and very irregular and etched grains have been produced.

A southeasterly decrease in sand content of the Conococheague in the area studied and similar trends in equivalent Gatesburg beds in Pennsylvania and the Copper Ridge dolomite of northeastern Tennessee and southwestern Virginia suggest that the source of the detritus was to the northwest.

INTRODUCTION

Arenaceous beds of the late Cambrian Conococheague formation are present at many localities throughout the outcrop area in the Appalachian Valley area of Pennsylvania, Maryland, West Virginia, Virginia, and Tennessee. These are the only sandy beds in about 8000 feet of carbonate sediments from the Lower Cambrian to the Middle Ordovician in northern and central Virginia and hence are important for mapping purposes as well as for sedimentological research. In spite of their importance and distinction in lithology from the enclosing strata, no detailed petrographic or stratigraphic study has been made of the beds over the general area described in this paper. However, Krynine (1941) and Prouty (1948) studied, petrographically, equivalent beds in Pennsylvania and Tennessee, respectively, and Wilson (1952) has made a general stratigraphic study of the Upper Cambrian in the central Appalachians.

Sections of the Conococheague in Augusta, Rockingham, Shenandoah, Page, Frederick, Clarke, and Warren counties over a distance of about 100 miles were examined and measured in detail, and samples were collected for laboratory analyses. Thin sections and heavy mineral concentrates were used to determine the petrographic character and the sources of the arenaceous beds.

The writer wishes to express his appreciation to Dr. H. A. Ireland of the University of Kansas for his criticism of the manuscript and for his supervision of the study. Dr. Raymond S. Edmund-

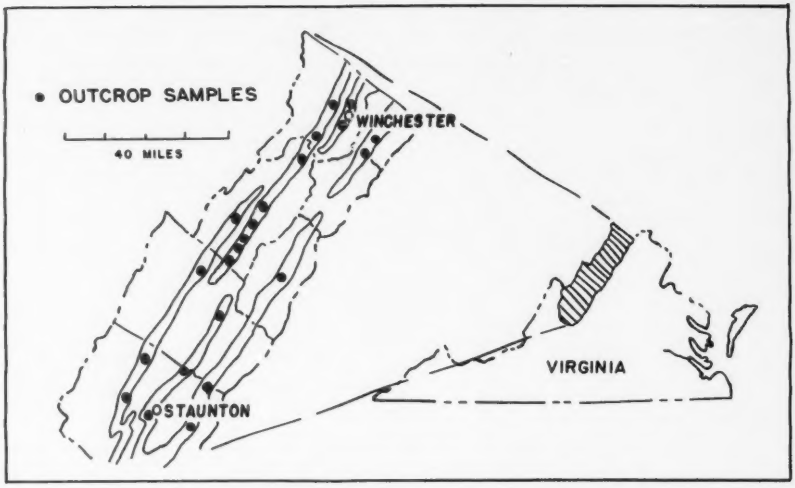

FIG. 1.—Distribution of Conococheague formation and location of samples.

son of the University of Virginia gave helpful advice during the course of the field work and Dr. James Lee Wilson of the Shell Research Laboratory, Houston, Texas, read and criticized the manuscript. Miss Ada Swineford of the State Geological Survey of Kansas aided in identifying some of the heavy minerals.

STRATIGRAPHY

Arenaceous beds of the Conococheague formation crop out in one or more belts in the Appalachian Valley in central and northern Virginia (fig. 1). They range in thickness from less than 1 foot to as much as 8 feet and are variously bedded, from thinly laminated to massive. The sandy beds are interbedded with about 2000 feet of argillaceous and impure limestones and dolomites typical of the Conococheague. The contact between the two types of rock is fairly sharp in most cases, although there are gradations between the two types of sediments with sand grains scattered in the enclosing carbonates. The sandy beds are restricted to a lower clastic portion of the formation named the Big Spring Station member by Wilson (1952) and to an upper clastic phase which is not differentiated as a named member. Both sandy phases are exposed in the westernmost and central belts in the Appalachian Valley whereas only a few thin sandy beds are exposed along the easternmost outcrops, which lie a maximum distance of about 30 miles to the east. In contrast to this directional thinning to the east, there is a general lateral persistence to the northeast-southwest in the thickness of the two clastic phases.

According to Butts (1940), the sandstones of the Conococheague are irregularly distributed both vertically and horizontally through the formation. Prouty (1948) also mentions that the sandy zones occur at various horizons throughout the formation in Virginia and Pennsylvania. However, in the area studied by the writer, the arenaceous beds have a definite pattern and position in the formation. There is considerable lensing and variation in thickness of individual beds and it is very rarely that a particular sandy bed can be traced over a few miles along the strike. Usually the

continuity is limited to less than 1 mile

Most of the sandy units are cross-bedded to some degree and in places have several distinct zones of tabular cross-bedding within a single bed in which the herringbone-type structure indicates completely opposite directions of currents. Other evidence of shallow-water deposition are local occurrences of ripple marks and mud cracks as well as sandy intercalations in adjacent beds of intraformational conglomerate.

The Conococheague is regionally correlated with the Gatesburg formation of central Pennsylvania and the equivalent Copper Ridge dolomite to the southwest in Virginia and Tennessee, both of which contain sand in greater amounts than is present in the Conococheague.

PETROLOGY

Thin sections of about 80 samples from 22 localities (fig. 1) were examined and it was found that the arenaceous beds consist of orthoquartzites with silica as the cementing material and calcareous sandstones containing calcite as the cement. The two types are about evenly divided in distribution and never occur together in the same thin section.

The dominant mineral constituent of the beds is quartz with very minor amounts of chert fragments and heavy mineral accessories constituting less than 1 percent of the total samples. Scattered calcareous oolites were also observed in several of the calcareous sandstones. The quartz of the calcareous sandstones is uniform and similar in most samples, whereas several types are present in the orthoquartzites. In the latter rock, about 75 percent of the quartz is normal clear igneous quartz (Krynine, 1940, p. 15). It contains no strain shadows and few inclusions. Subordinate to the igneous type is a variety with strong undulose extinction and many inclusions, which under Krynine's classification would be called modified igneous quartz or possibly a metamorphic variety. Scattered grains of this type were also found in the calcareous sandstones but are not nearly as abundant as in the orthoquartzites.

FIG. 2.—Strain shadows in quartz grain of an orthoquartzite oriented much like a pseudo-microcline grid. ×100 crossed nicols.

The strain shadows of these grains is readily visible under the microscope. In a few grains the extinction is oriented much like that of a pseudo-microcline grid, and it may be easily confused with microcline (fig. 2).

No definite fabric or pattern in the arrangement of the quartz grains was observed in any of the thin sections.

Most of the quartz grains in the calcareous sandstones are well-rounded and frosted. The range of grain sizes does not indicate a high degree of sorting; however, 27 histograms do show moderately good sorting, the average grain size ranging from .25 mm to .50 mm. The orthoquartzites are less well-sorted, though some of the apparent poor sorting is probably due to secondary enlargements which have masked the detrital cores.

The histograms of the calcareous sandstones do not indicate any directional coarsening or significant vertical differences in the grain size distribution.

CALCITE-CEMENTED SANDSTONES

In most beds with the calcareous cement, the well-rounded quartz grains

appear to have been dropped into the matrix as "plums in a pudding" and the result is a rock containing floating or widely separated quartz grains embedded in calcium carbonate. As a consequence, the packing of the grains is extremely poor and very few of the grains are in contact with each other. The proportion of calcareous cement to detrital quartz ranges from 13 to 35 percent, the average being 22 percent by weight of the total sample. The calcareous material is invariably in the form of calcite which completely fills all pore spaces and ranges in character from finely granular or microcrystalline to subhedral grains with well-developed rhombohedral cleavage and fair twinning. The calcite in the form of rhombohedra is generally found in the comparatively loose sands in the larger pore spaces where it has developed without interference of adjacent sand grains. The optical orientation of the calcite crystals seems to be random in all samples examined.

The granular type of calcite is fine-textured but has irregular and interlocking outlines and forms a crystalline mosaic between grains. In some slides the two types of calcite occur together but are distinctly separated (fig. 6).

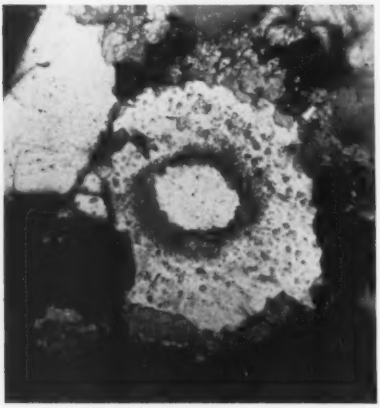

FIG. 3.—Secondary enlargement of quartz grain in a calcareous sandstone. The boundary of the slightly etched detrital grain is outlined by a halo of engulfed carbonate inclusions. ×100 crossed nicols.

A very few grains in the calcareous sandstones have been enlarged secondarily but without construction of the euhedral crystal form. The boundary of the original detrital grain is outlined in most cases by a halo of carbonate inclusions which represents engulfed carbonate material from an earlier matrix (fig. 3).

REPLACEMENT OF QUARTZ BY CALCITE

In many samples the original quartz has been corroded markedly and has been replaced by the calcite cement. Such replacement has been reported previously (Hatch, Rastall, and Black, 1938 p. 229; Krynine, 1940, p. 24; Swineford, 1947, p. 84–85; Pettijohn, 1949, p. 484; and others), but it has generally been recognized as uncommon and its significance overlooked. However, examination of about 50 thin sections of calcareous sandstones from the Conococheague discloses that there is hardly a slide which does not contain at least several grains which have been etched and corroded by the calcite cement (fig. 4). In the Conococheague then this process may be regarded as a relatively common feature. No evidence of replacement of quartz was observed in the orthoquartzites.

Very jagged and irregular-shaped grains have been formed by this corrosion. It is obvious that such grains with the very delicate and irregular angular edges (fig. 5) could not have been transported without such edges being broken off. It is concluded that these grains are the result of post-depositional replacement. When the loose grains are examined microscopically, it is apparent that the grains were fairly well-rounded when originally deposited.

Several stages in the replacement of quartz by calcite are evident, ranging from minutely corroded grains to residual rings of unaltered material representing the original grain. Replacement of the

grain proceeds from the outer edge of the grain inward, advantage being taken of existing cracks and cavities. Generally, the calcite immediately adjoining the quartz grain is coarser-grained than neighboring calcite, and a very narrow rim of this coarser cement, at places subhedral, may encircle the quartz. Locally, spots or blobs of coarser-grained calcite appear in the midst of large areas of finer-grained calcite. Some of these blobs contain minute fragments of quartz. It is probable that these outlines or "ghosts" represent grains of quartz which have been replaced completely, or they may be due, in part, to the line of transection of the thin section. The fact that several stages of corrosion may be seen, however, lends support to the former conclusion in most cases. The sequence is seen to begin with grains showing very early stages of corrosion and minute etching and to end with small scattered fragments of quartz which are the remnants of much larger original grains.

The continual replacement of quartz by calcite has reduced the number and size of quartz grains and increased the relative percentage of calcite. This replacement may be in part responsible for the loose packing and wide spacing of quartz grains observed in thin sections. If this process should be carried to com-

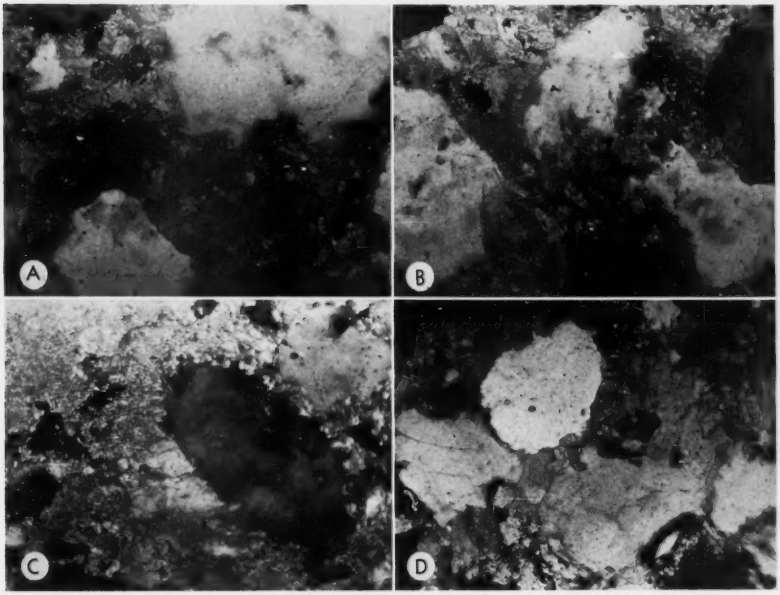

FIG. 4.—Photomicrographs of Conococheague sandstone thin sections showing replacement of quartz by calcite. ×65 crossed nicols. A.—Large quartz grains in a coarsely crystalline cement. Quartz has ragged edges resulting from replacement by calcite. B.—Irregular and angular edged quartz. Note the large re-entrant of calcite into the grain in the center. C.—A calcareous sandstone composed of rounded quartz grains markedly etched and corroded by the fine-grained and microcrystalline calcite cement. Extended segments of large grain in the center have been nearly separated from the parent grain and smaller fragments of quartz on the left have been almost completely replaced. D.—Etched grains of quartz with large re-entrants of coarsely crystalline cement. Some of the grains show more replacement than others.

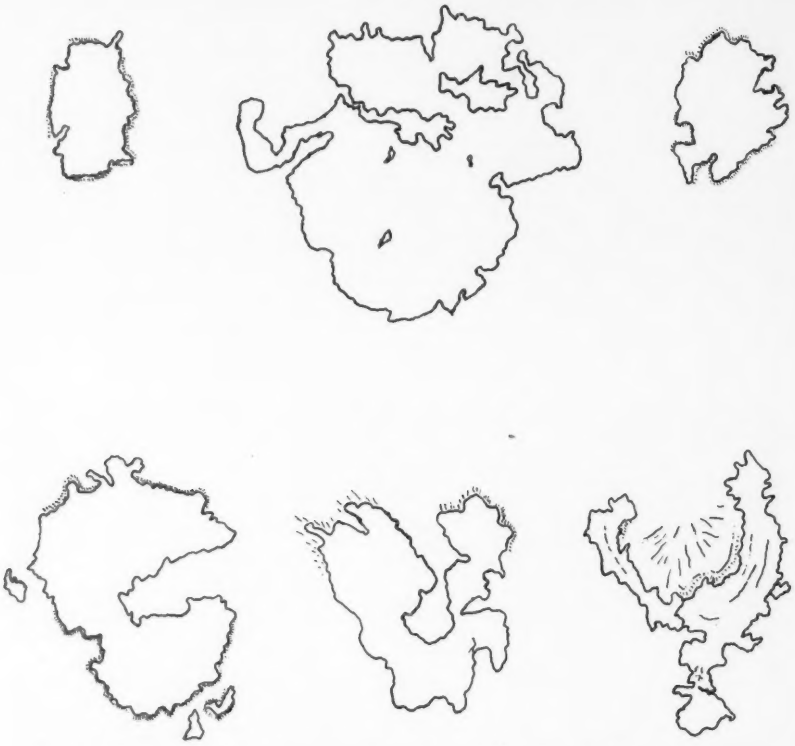

FIG. 5.—Camera lucida drawings of quartz grains in thin section showing various stages in the replacement by calcite. ×65.

pletion in each stratigraphic unit, it is conceivable that the sandstone would be replaced until only calcite remained.

SILICA-CEMENTED SANDSTONE

The orthoquartzites containing silica as the cementing material are characterized by considerable secondary enlargement with the secondary quartz being in optical continuity with the detrital grains. In a few places almost every grain is secondarily enlarged. Some quartz grains have nearly perfect crystal boundaries with well-developed pyramidal structures, but more commonly the straight sutures between grains result from the preservation of newly formed crystal faces. Where the cemented grains grew so closely together that they mutually interfered and prevented the development of crystal faces, no euhedral or subhedral grains were formed. This is true of most of the orthoquartzites where the secondary enlargment of the quartz grains has produced apparent angularity of these grains. This interlocking or welding of the original detrital grains by secondary growth creates a very dense and tight rock in which all voids are filled by silica. The space occupied by the ce-

ment is less than in the carbonate cemented samples.

It is likely that in the few samples where the original grain cores are apparently interlocked or welded together, it is the result of solution of the quartz at points where grains are in contact with each other (Waldschmidt, 1941).

Boundaries between the nuclei and secondary enlargements are defined in most grains by a thin dusty line or coating of an iron oxide which represents the outline of the original detrital grain. Such grains do not show the etching which is characteristic of the calcite-cemented sandstones. This dusty line is especially well seen in those grains which have euhedral or subhedral overgrowths, but is poorly defined in grains with irregular angular enlargements. The secondary silica growth is typically clear and resembles the original grain in color.

Uncommonly a quartz grain is surrounded by a thick rim of chalcedony which may be recognized by the microcrystalline texture and a color darker than the normal secondary quartz. The chalcedony is surrounded by the calcite matrix (fig. 6).

HEAVY MINERALS

Heavy minerals were extracted from the calcareous samples using the standard procedures of sedimentary petrography. Identification of the grains was made and the mineral percentages computed by grain counts. The heavy minerals are divided into two groups, allogenic and authigenic.

Allogenic Minerals

Tourmaline is a very protean and ubiquitous mineral. Not only does it occur in every rounded shape imaginable, but it is found in at least ten different varieties based on color. All grains are well-rounded but the rounding is most perfect in the larger sizes. The shape ranges from elongate water-melon-shaped grains to oval globular types. Many grains show fine etching or pitting when viewed with a high power objective. Inclusions are not common (fig. 7).

In many samples the tourmaline grains have developed secondary overgrowths. The enlargements are in optical continuity with the original rounded detrital grain and have well-developed termina-

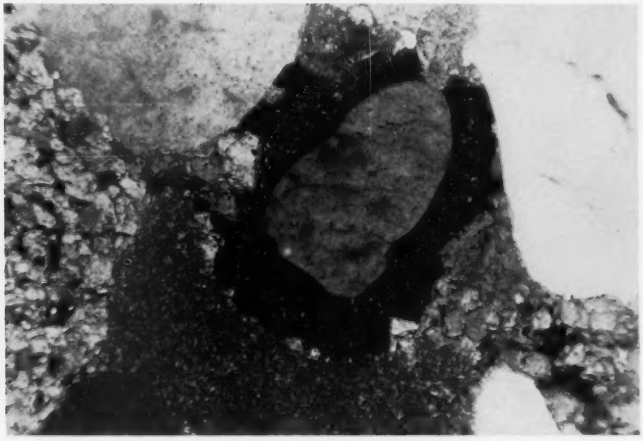

FIG. 6.—Rounded grain of quartz enclosed in a darker rim of chalcedony in calcite matrix. Note the sharp boundary between the coarse and fine-grained calcite. ×100 crossed nicols.

FIG. 7.—Heavy minerals from Conococheague sandstones. A. Rounded zircon showing considerable abrasion. ×75. B. Typical assemblage of rounded tourmaline, some of which has minor development of secondary overgrowths. ×56.

tions which rarely exceed 25 percent of the original grain. Most of the overgrowths are confined to one end of a grain although some have growths on both ends, and a few show enlargement along the sides of an elongate grain parallel to the *C* axis.

The edges of some enlargements are angular but others are well-worn. The angular growths terminate in slender splintery extensions and appear to be very fragile. This is in contrast to the

worn overgrowths which have smoothed edges.

Zircon ranges in color from clear to a faint pinkish tinge and occurs as long slender or oval-shaped grains with well-rounded terminations (fig. 7). Next to tourmaline, zircon is the most abundant mineral and like tourmaline, it maintains a very uniform character in all samples.

Fluorite occurs as colorless subangular grains which are only slightly worn.

Garnet may be recognized as irregular dark-red grains with conchoidal fracture and sharp angular edges. The surfaces of the grains are pitted and etched indicating corrosion.

Hornblende occurs as dark to pale green subangular grains with the characteristic cleavage moderately well-developed. Significantly the mineral appears very fresh and unaltered though a few grains have worn edges indicating slight abrasion.

Muscovite exists in a number of samples as thin transparent gray to white flakes with low relief. The flakes are moderately rounded and the somewhat frayed edges turned upwards cause the rim to have a higher order of interference colors than the central part of the grain.

Biotite consists of deep-brown grains or flakes ranging from round to slightly hexagonal in outline. It is less abundant than muscovite.

Rutile is characterized by deep brownish-red grains, most of which are subangular. A few grains have geniculated twinning.

Topaz, found in a few samples, is a relatively minor mineral. It is colorless to slightly bluish and generally occurs as subangular grains containing numerous colorless inclusions.

Kyanite is tentatively identified in three samples. It is present as colorless, rounded elongate grains with a very poor development of rectangular cleavage.

Andalusite occurs in only two samples and consists of worn colorless grains with fair prismatic cleavage.

Ilmenite grains are very uncommon. They occur as opaque, subangular particles with a metallic luster and a deep purplish sheen in reflected light.

Staurolite is present as straw-yellow and hackly angular grains containing numerous inclusions. The grains show marked pleochroism.

Magnetite is identified by its magnetic properties and black color. The grains are well-rounded and show much wear. It is present in only one sample.

Authigenic Minerals

Pyrite occurs as floods in almost all the samples. It may be distinguished by the euhedral cubes and pyritohedrons, which are usually striated, and the characteristic pale brass-yellow color.

Leucoxene is present in a few samples as dull-white, opaque, rounded, porous masses.

Barite is identified tentatively as very ragged and irregular grains. It is very uncommon.

Hematite and limonite are grouped together as they are closely associated in the samples and the distinction between the two is not always possible. The minerals occur as irregular and earthy masses and as inclusions in the calcite cement. The reddish or brownish-yellow stain derived from the minerals may be seen as coating on many other minerals.

Zircon is detrital in every sample except one where it occurs as pinkish to clear euhedral grains with distinct crystal faces (fig. 8).

Interpretation

Angular overgrowths on tourmaline and quartz and corrosion of quartz by calcite indicate that post-depositional chemical processes have been active in the sandy beds. These secondary processes have altered the texture of the rock by tightening the sandstones, producing a typical orthoquartzite texture. In contrast chemical attack on quartz by calcite has tended to destroy the quartz, resulting in a more calcareous rock. It is

FIG. 8.—Euhedral zircon from heavy mineral fraction of Conococheague sandstone. ×100.

significant, however, that hornblende, which is relatively unstable, appears fresh in all samples and has not been affected by any observable chemical alteration.

Many of the detrital minerals appear to have undergone only one brief cycle of erosin with very little transportation. This is indicated by the freshness and angularity of hornblende, garnet, topaz, and other minerals. Other heavy minerals such as tourmaline and zircon have been abraded considerably and suffered from prolonged movement. The abraded overgrowths suggest a prior sedimentary environment for at least part of the material. In addition it is quite probable that some of the well-rounded and stable minerals such as tourmaline and zircon not showing abraded secondary enlargements were derived from older sediments.

No significant vertical or lateral variations are noted in the distribution of the heavy minerals. The most obvious feature is the persistence of a few minerals such as tourmaline and zircon and local floods of a few relatively uncommon types such as hornblende, garnet, muscovite, biotite, and topaz from a few samples. According to Krynine (1941), the floods of angular and unstable minerals are due to contamination from "monadnocks" near the site of deposition.

In summary, the well-rounded tourmaline and zircon and the abraded overgrowths on the tourmaline suggest previous sedimentary deposition. The presence of chemically unstable hornblende, however, precludes the possibility that it is derived from an older sediment and suggests a nearby crystalline source. It is concluded, therefore, that a mixing of detritus from sedimentary and crystalline sources has occurred, supplying the constituents of the arenaceous beds of the Conococheague formation.

CONCLUSIONS

The arenaceous beds of the Conococheague are confined to two definite stratigraphic phases in the formation, one group occurring at or near the base of the formation and a higher phase near the top. The two groups are laterally persistent throughout the northern and central Appalachian Valley of Virginia, with the exception of the easternmost outcrops where only one thin sandy phase is present. This northwestward thickening of the sandy beds has been traced more extensively in the equivalent Gatesburg formation of central Pennsylvania (Swartz, 1950; Wilson, 1952) and in the equivalent Copper Ridge dolomite in southwest Virginia and northeast Tennessee (Prouty, 1948). The lateral persistence of the sandy phases along the general northeast-southwest strike of the formation suggests a somewhat linear source to the northwest subparallel to the synclinorium.

On the basis of the mineralogical composition of the sandy beds it is apparent that these beds represent the product of several cycles of deposition and erosion of older sediments. The high quartz index of the sediments indicates prolonged weathering and transportation of the detrital particles and a consequent reduc-

tion in the relatively unstable mineral species leaving a concentration of the more stable species such as tourmaline or zircon. The uniformity of composition and the occurrence of the beds as thin, widespread stratigraphic units over the central Appalachian area indicates that these sediments represent extensive stable, though irregular, conditions of sedimentation with considerable transport and winnowing action before final accumulation. In isolated localities, however, the environment was such as to produce a mixing of the pure quartz sand and relatively unstable minerals such as hornblende, resulting in an immature sediment.

While not conclusive, the persistence of approximately the same heavy minerals, without any radical change in percentages in both the upper and lower sandy phases, suggests that the two groups were derived from the same type of terrane. This is especially significant when it is recalled that the two sandy phases are everywhere separated by a thick sequence of carbonates, up to as much as 1000 feet, which represents an entirely different set of environmental and sedimentary conditions.

It appears that the calcareous cement was deposited penecontemporaneously with the sand. This is indicated by the restriction of the calcite-cemented sandstones to certain horizons and by the loose packing of the grains. In these beds the rare secondary silica enlargements are later than the calcite cement. This is seen in grains surrounded by secondary silica in which the original etched detrital core is outlined by a halo of engulfed carbonate inclusions.

It is possible that the larger, coarser, and subhedral type of carbonate seen in some of the thin sections has a clastic origin whereas the finer, microcrystalline carbonate apparently is the original cementing material. Such an interpretation is difficult to make in many cases, however, because the clastic carbonate readily dissolves and reprecipitates leaving little if any trace of its clastic origin. In such cases of mixed carbonate and quartz detritus where the quartz exceeds 50 percent of the rock, the rock may be called a calcarenaceous orthoquartzite.

The absence of any etching of quartz grains in the silica-cemented sandstones suggests that the silica cement is primary also. In addition, the cores of grains are rarely found in contact; instead nearly all are separated by the secondary enlargements surrounding the grains. The detrital grains must have been separated at the time of deposition or at least before compaction took place.

The replacement of quartz by calcite apparently is responsible for the irregular and etched surfaces of many of the grains. Much of the frosting and etching of grains which has been ascribed previously to transportation is probably the result of the corrosion and replacement of the quartz by calcite.

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FIGS. 1–9, MARCH, 1956

A NEW METHOD OF EXPRESSING PARTICLE SPHERICITY[1]

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ABSTRACT

For a more complete characterization of the shape of sedimentary particles, a method for tridimensional shape analysis is described. It is proposed to return to Wadell's original definition of sphericity, i.e., the degree of true sphericity, as the basis for the quantitative description of shape. However, instead of analyzing each grain form as such, the shape is approximated by a tetrakaidekahedron which is defined by three mutually perpendicular particle dimensions. Using these measured dimensions and the geometric characteristics of the tetrakaidekahedron, the shape of particles can be defined simultaneously in terms of Wadell's sphericity and Zingg's shape factor. An expression is derived for approximating the degree of true sphericity of sedimentary particles. It is shown that the use of this expression as the "working sphericity" seems to be justified and may be considered an improvement over other approximations. An example of the workability of the technique is given by the tridimensional shape analysis of the component grains of a sample of Woodbine sandstone. It is thought that the method described can be of use in many phases of stratigraphic and sedimentary research.

INTRODUCTION

Together with size, surface texture, and mineralogical composition, shape is recognized as one of the fundamental properties of sedimentary particles. The shapes of component grains of a sediment express part of the sedimentary history and are related to porosity and permeability.

As early as 1880 Sorby developed a classification of sand grains which involved the concept of shape. In 1919 Wentworth introduced the first quantitative system for measuring the shapes of sedimentary particles. Subsequently several quantitative methods for expressing shape were evolved by Cox (1927), Hagerman (1933), Krumbein (1941), Pentland (1927), Tickell (1941), Wadell (1932, 1933, 1935), Wentworth (1919, 1922, 1922a), and Zingg (1935), among others.

Of the various definitions of shape none seems to have found such wide recognition and acceptance as Wadell's concept of sphericity (Wadell, 1932), which can be expressed as

$$\psi = \frac{S_S}{S_P}$$

where

ψ = degree of true sphericity
S_P = surface area of the particle
S_S = surface area of the sphere of the same volume.

In practice ψ cannot be determined since this would imply a complicated integration over surface elements of an irregular particle. Wadell realized this difficulty and developed (mainly for large particles) a practical formula or operational definition of sphericity (Wadell, 1933) which can be expressed as

$$\psi_{OP} = \sqrt[3]{\frac{V_P}{V_{CS}}}$$

where

ψ_{OP} = operational sphericity
V_P = volume of the particle
V_{CS} = volume of the circumscribing sphere.

Much of the subsequent work on sphericity, notably by Wadell and by Krumbein (1941), was based on the operational

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definition, and hence operational sphericity has become almost synonymous with sphericity. The method described in this paper is a return to Wadell's original definition of the degree of true sphericity as the basis for quantitative shape analysis.

It is proposed to analyze the shape of sedimentary particles tridimensionally. However, instead of analyzing each irregular grain form as such, the shape is approximated by a tetrakaidekahedron, a solid easy to handle mathematically and smooth enough to approximate rounded forms sufficiently well. The tetrakaidekahedron is defined by three mutually perpendicular parameters derived from tridimensional intercept measurements of grains.

The first part of this paper deals with the use of the three-dimensional measurements in order to express the shapes of the particles. The application of the method to the shape analysis of the component grains of a sandstone sample is demonstrated in the second part. Various pertinent details are presented in the appendix.

TRIDIMENSIONAL SHAPE ANALYSIS

Definition of the Approximating Body

In order to obtain three mutually perpendicular parameters the following grain dimensions are measured:

H = height of the particle = vertical distance of the highest point of the grain from the base on which the grains are strewn,

L = longest apparent intercept of the particle parallel to the base plane,

M = longest chord of the grain parallel to the base plane and perpendicular to L.

The writer used a photogrammetric method for the tridimensional measurement of sand grains in connection with this study (Aschenbrenner, 1955). However, these measurements can be made by various techniques depending on the size of the particles (Huitt, 1954; Krumbein, 1941).

After obtaining the three mutually perpendicular dimensions H, L, and M, these are oriented with respect to the orthogonal Cartesian coordinate axes X, Y, and Z as follows: whichever of the three intercepts is longest becomes parameter $2a$ along the X-axis, the shortest becomes $2c$ along the Z-axis, and the intermediate dimension becomes $2b$ along the Y-axis; a, b, and c are half-axes and are the parameters which define the approximating body, the tetrakaidekahedron. The scheme outlined above avoids problems arising from the orientation of the grains and warrants dealing hereinafter with the half-axes a, b, and c alone as parameters.

Geometry of the Approximating Body

It was pointed out previously that the tetrakaidekahedron is used as the approximating body since it is easily handled mathematically and smooth enough for approximating rounded forms. It is thought to be superior to the triaxial ellipsoid not only because the calculation of the surface area of the ellipsoid is rather involved (see Appendix V), but also because sedimentary particles, especially sand grains, as a rule do not have perfectly smooth surfaces.

The tetrakaidekahedron in its simplest form is one of the thirteen Archimedean bodies which is derived by truncating the cube or the octahedron, two of the five Platonic bodies. If a cube with the half-axes a, b, and c, where $a=b=c$, is truncated by an octahedron with the half-axes $\frac{1}{3}a$, $\frac{1}{3}b$, and $\frac{1}{3}c$, where $a=b=c$, a tetrakaidekahedron with 14 equilateral facets is obtained. This solid with six square and eight hexagonal faces was named by Lord Kelvin the orthotetrakaidekahedron (Thompson, 1943) (fig. 1). Its half-axes are a, b, and c, where $a=b=c$. By expanding the orthotetrakaidekahedron differentially along the X, Y, and Z axes, a tetrakaidekahedron is obtained which is bounded by three pairs of equal and opposite quadrilateral faces and by four pairs of equal and opposite hexag-

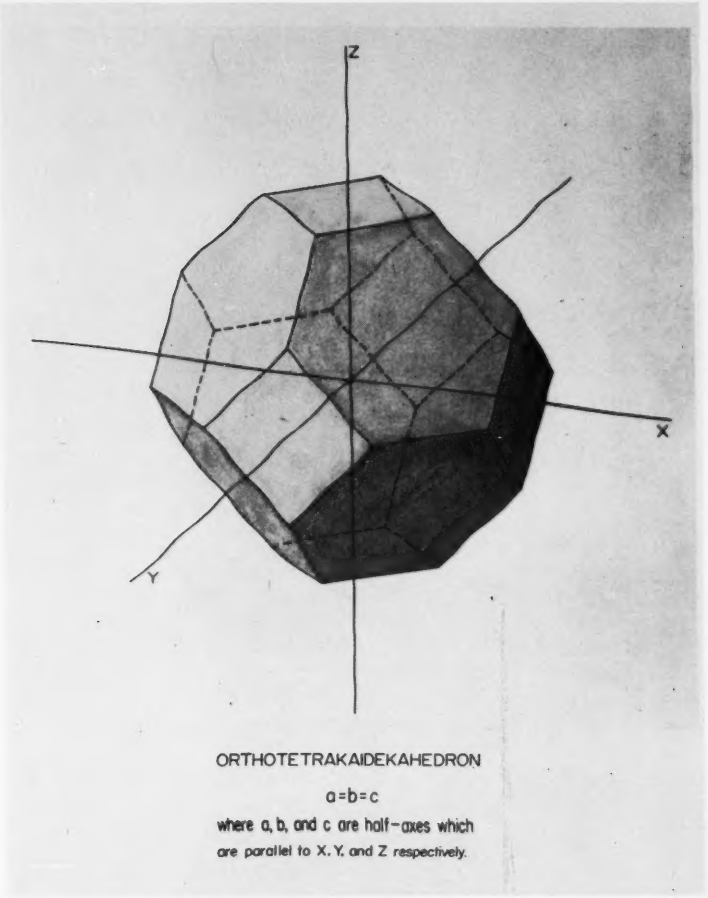

FIG. 1.—Orthotetrakaidekahedron in dimetric projection.

onal faces (fig. 2). Its half-axes are a, b, and c, where $a>b>c$. The surface of a tetrakaidekahedron with the half-axes a, b, and c, where $a \geqq b \geqq c$, can be expressed in terms of these parameters as

$$S_T = ab+bc+ca+6\sqrt{a^2b^2+b^2c^2+c^2a^2}$$

(see Appendix I).

The volume of the tetrakaidekahedron is expressed as

$$V_T = 4abc \quad \text{(see Appendix II)}.$$

Definition of Shape

Although Wadell's degree of true sphericity cannot be determined in practice, it can be approximated by various

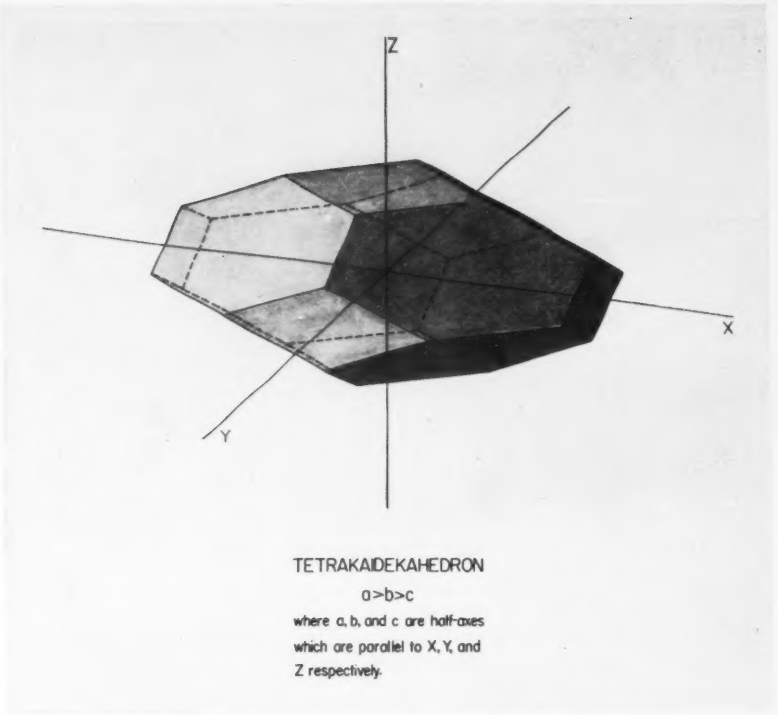

FIG. 2.—Tetrakaidekahedron in dimetric projection.

methods. One line of approach, used in this paper, is to approximate the irregular sedimentary particle by a solid whose surface area can be expressed in terms of easily measurable parameters. Using the tetrakaidekahedron as the approximating body, the true sphericity is approximated by

$$\psi'_S = \frac{S_S}{S_T}$$

where

S_T = surface area of the tetrakaidekahedron which is defined by the three measurable, mutually perpendicular dimensions of the particle

S_S = surface area of the sphere of the same volume as the tetrakaidekahedron.

Since the surface area, true or approximated, is the only attribute introduced into Wadell's concept, aside from the volume, particles of different "flatness" and "elongation" can have the same sphericity. This was pointed out by Krumbein (1941) who consequently combined sphericity with an expression of shape based on intercept ratios developed by Zingg (1935). The method described in this paper lends itself well to expressing the shape of the measured particle in terms of Wadell's and Zingg's classifications since both sphericity ψ and shape

factor F can be expressed in terms of a, b, and c. Following Zingg's terminology, F can be expressed as the ratio of the

$$\left(\frac{\text{short dimension}}{\text{intermediate dimension}}\right)=p=\frac{c}{b}$$

to the

$$\left(\frac{\text{intermediate dimension}}{\text{long dimension}}\right)=q=\frac{b}{a}$$

thus

$$F=\frac{p}{q}=\frac{ac}{b^2}.$$

Substituting p and q for c/b and b/a respectively (see Appendix III), the degree of true sphericity may be approximated by

$$\psi'_S=\frac{S_S}{S_T}=\frac{12.2\sqrt[3]{p^2q}}{1+p(1+q)+6\sqrt{1+p^2(1+q^2)}}.$$

However, ψ'_S can never attain the numerical value 1.0, which is the limiting value of the true sphericity. Therefore, the surface area of the orthotetrakaidekahedron of equal volume, S_{OT}, is substituted for S_S (see Appendix IV) and the true sphericity is then approximated by

$$\psi'_T=\frac{S_{OT}}{S_T}=\frac{13.4\sqrt[3]{p^2q}}{1+p(1+q)+6\sqrt{1+p^2(1+q^2)}}.$$

Using this last expression, an actually existing particle of the shape of an orthotetrakaidekahedron would be given the sphericity 1.0 instead of its true sphericity of 0.91. Yet, particles of almost spherical shape and at the same time with such prominent edges as the orthotetrakaidekahedron are not likely to occur in nature; neither are perfect spheres. Therefore, the best approximation of the true sphericity is perhaps somewhere between ψ'_S and ψ'_T, and it is a matter of judgment which value is chosen. If the "working sphericity" ψ' is arbitrarily set half-way between ψ'_S and ψ'_T, the degree of true sphericity is then approximated by

$$\psi'=\frac{12.8\sqrt[3]{p^2q}}{1+p(1+q)+6\sqrt{1+p^2(1+q^2)}}.$$

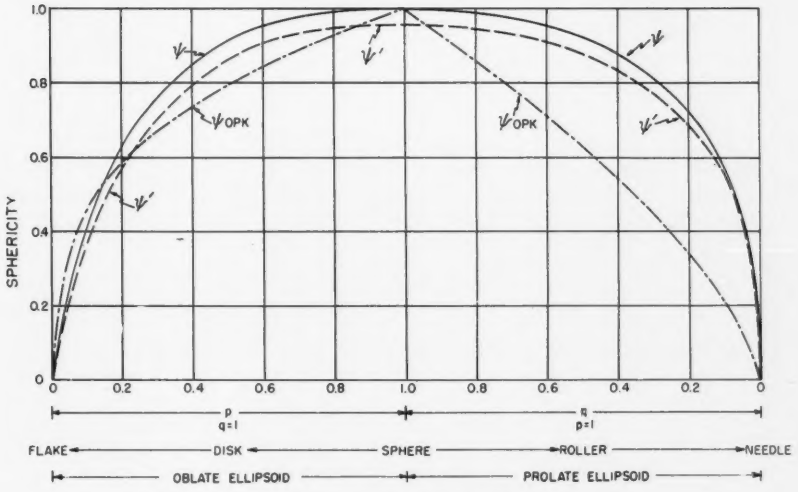

FIG. 3.—Sphericities of a series of ellipsoids of rotation.

TABLE 1.—*Comparison of ψ' with the true sphericity ψ for various angular and rounded solids*

Solid	Half-axes			Shape Factor F	True Sphericity ψ	Approximation ψ'	% Error
	a	b	c				
Prismatic Rod length = 4; width = 2; height = 2	2.24	1.12	1	1.79	0.77	0.87	+13.0
Quadratic Plate sides = 4; height = 2	2.83	2.83	1	0.35	0.76	0.76	± 0
Cylindrical Plate diameter = 4; height = 2	2	2	1	0.50	0.83	0.86	+ 3.6
Triaxial Ellipsoid	2.5	2	1	0.63	0.88	0.83	− 5.7
Triaxial Ellipsoid	2.5	1.5	0.75	0.83	0.83	0.78	− 6.0
Prolate Ellipsoid	2	1	1	2.0	0.93	0.88	− 5.0
Prolate Ellipsoid	3	1	1	3.00	0.85	0.81	− 4.7
Oblate Ellipsoid	2	2	1	0.50	0.91	0.86	− 5.5
Oblate Ellipsoid	3	3	1	0.33	0.80	0.75	− 6.3
						Root-mean-square error	± 6.4%

Evaluation of ψ'

The ultimate test of any approximation of the degree of true sphericity would be a comparison of the results with the values obtained by a method which actually measures the surface areas of irregular solids. Although some physiochemical methods may lend themselves to such an investigation, the scope of the study described in this paper does not permit an analysis of this possibility.

In order to show sufficient approximation of the true sphericity by the more or less arbitrary expression for ψ', the true sphericities of rounded and angular solids are compared with the approximated values. The results are summarized in table 1, and it can be seen that ψ' is a good approximation of the true sphericities of the solids considered.

Another interesting comparison is obtained by using the tetrakaidekahedron as the reference solid instead of the triaxial ellipsoid which is used by Krumbein (1941) in the expression for operational sphericity

$$\psi_{OPK} = \sqrt[3]{\frac{bc}{a^2}} = \sqrt[3]{q^2 p}.$$

Substituting the tetrakaidekahedron for the ellipsoid the above expression becomes

$$\psi_{OPKT} = \sqrt[3]{\frac{3}{\pi}} \cdot \frac{2}{\sqrt{4+q^2}} \cdot \sqrt[3]{q^2 p}$$

$$= 0.9847 \cdot \frac{2}{\sqrt{4+q^2}} \cdot \psi_{OPK}$$

(see Appendix VI).

The sphericity values obtained after the substitution should agree closely with those obtained with the original formula. After solving the above expression for various values of q (see Appendix VI), the formula can be simiplified to

$$\psi_{OPKT} = (0.936 \pm 0.056) \cdot \psi_{OPK}.$$

This shows that the tetrakaidekahedron as the reference solid gives results slightly smaller but within a few percent of those obtained with the ellipsoid. The smaller values are of course due to the fact that the tetrakaidekahedron is more angular than the triaxial ellipsoid.

It seems equally interesting to evaluate the reversal of the substitution just described. If the triaxial ellipsoid is used as the approximating body instead of the tetrakaidekahedron, the following ex-

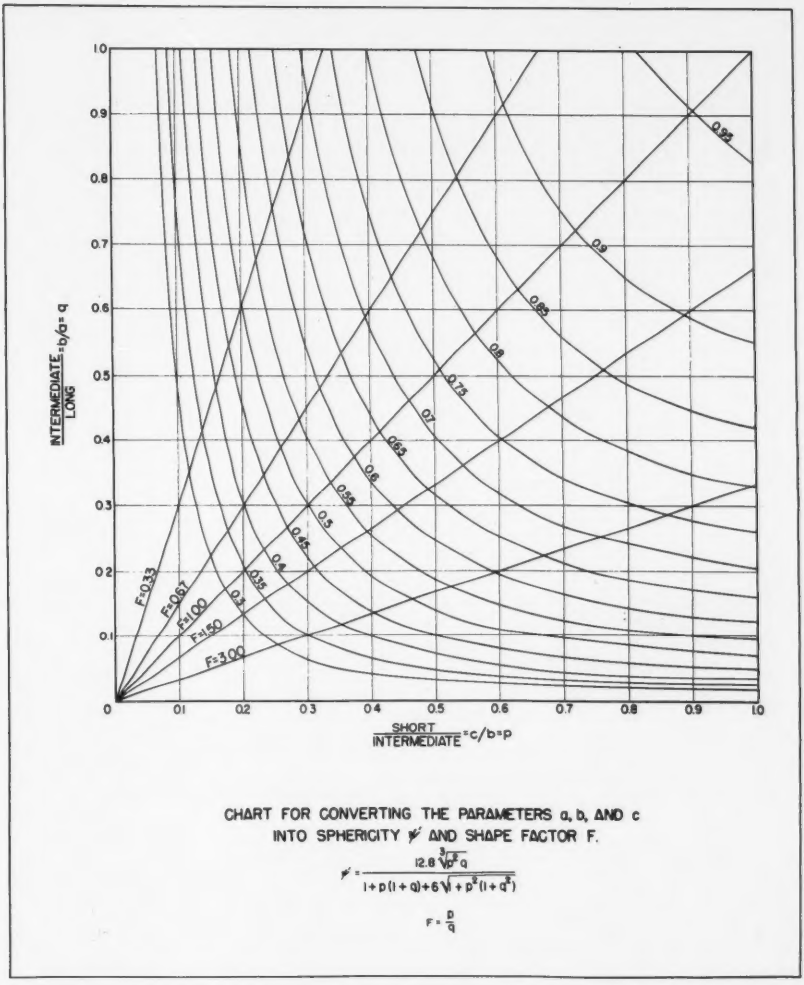

FIG. 4.—Chart for determining the shape of particles in terms of sphericity ψ' and shape factor F. Since ψ' is based on Wadell's definition of the degree of true sphericity, the lines of equal sphericity in this figure differ from curves of similar appearance which represent equal operational sphericities in charts resembling figure 4.

pression based on the definition of true sphericity, can be derived (see Appendix V)

$$\psi'_E = \frac{S_S}{S_E} = \frac{2\left(\frac{p}{q}\right)^{2/3}}{p^2 + \frac{1}{q \sin \gamma}\left[\sin^2 \gamma E(\gamma, K) + \cos^2 \gamma F(\gamma, K)\right]}$$

where

S_E = surface area of the triaxial ellipsoid

S_S = surface area of the sphere of equal volume

$K = \sqrt{1 - p^2/1 - p^2 q^2}$

$\gamma = \cos^{-1} pq$

F and E = elliptic integrals of the first and second order respectively.

A comparison of the ψ'_E values with the ψ' values for fifteen ellipsoids of rotation and four triaxial ellipsoids shows that the root-mean-square error of the ψ' values is 5.8 percent, with the maximum and minimum errors being -9.3 percent and -4.2 percent respectively (see Appendix VII). Obviously the sphericity values obtained with the tetrakaidekahedron as the reference solid, although consistently smaller, agree closely with those obtained using the triaxial ellipsoid as the approximating body. The size of the error, the complexity of the expression for ψ'_E, and the rarity of truly ellipsoidal forms among sedimentary particles are strong arguments in favor of using the tetrakaidekahedron as the reference solid.

If sphericity, which is considered to be a physically meaningful parameter of particle shape (Pettijohn, 1949), is ideally measured by the degree of true sphericity, then one is justified to ask how well the "working sphericity" ψ' approximates this ideal measurement and whether the method and expression described in this paper constitutes an improvement over other approximations such as the operational sphericity. In an attempt to answer these questions, the true sphericities ψ, the "working sphericities" ψ', and Krumbein's operational sphericities ψ_{OPK} are plotted for a group of ellipsoids of rotation in figure 3. This graph shows clearly the following facts:

1. ψ' follows the true sphericity ψ very closely, being consistently slightly smaller due to the fact that it takes into account a small angularity instead of the utmost smoothness represented by the ellipsoids.

2. ψ_{OPK} represents a parameter of entirely different behavior due to the fact that Krumbein's expression is based on the operational definition of sphericity. The characteristic differences as compared with the true sphericity are:

a. The ψ_{OPK}-curve has a cusp at the center where the ψ-curve has a horizontal tangent;

b. The slope of the ψ_{OPK}-curve on either side of the center stays nearly constant down to a value of 0.1 for p or q (i.e. ten times elongation or compression), while the slope of the ψ-curve increases slowly from 0 at the center to greater and greater values. Compared to the behavior of ψ_{OPK} the behavior of ψ' is more like that of the ideal measurement, the degree of true sphericity ψ; therefore the expression for ψ' is considered an improvement over expressions based on the operational definition of sphericity, such as ψ_{OPK}.

From the results of the various comparative studies described above it is concluded that the return to Wadell's original definition of sphericity as the basis for quantitative shape analysis is justified and that the use of ψ' as the "working sphericity" is warranted.

Procedure for Shape Analysis

In order to expedite the determination of the shape of sedimentary particles, a chart for converting the parameters a, b, and c into sphericity ψ' and shape factor F was prepared (fig. 4). Using this chart the problem of classifying the component grains of a sediment as to their shape is reduced to the following steps:

a. measuring the dimensions of a plurality of sedimentary particles,

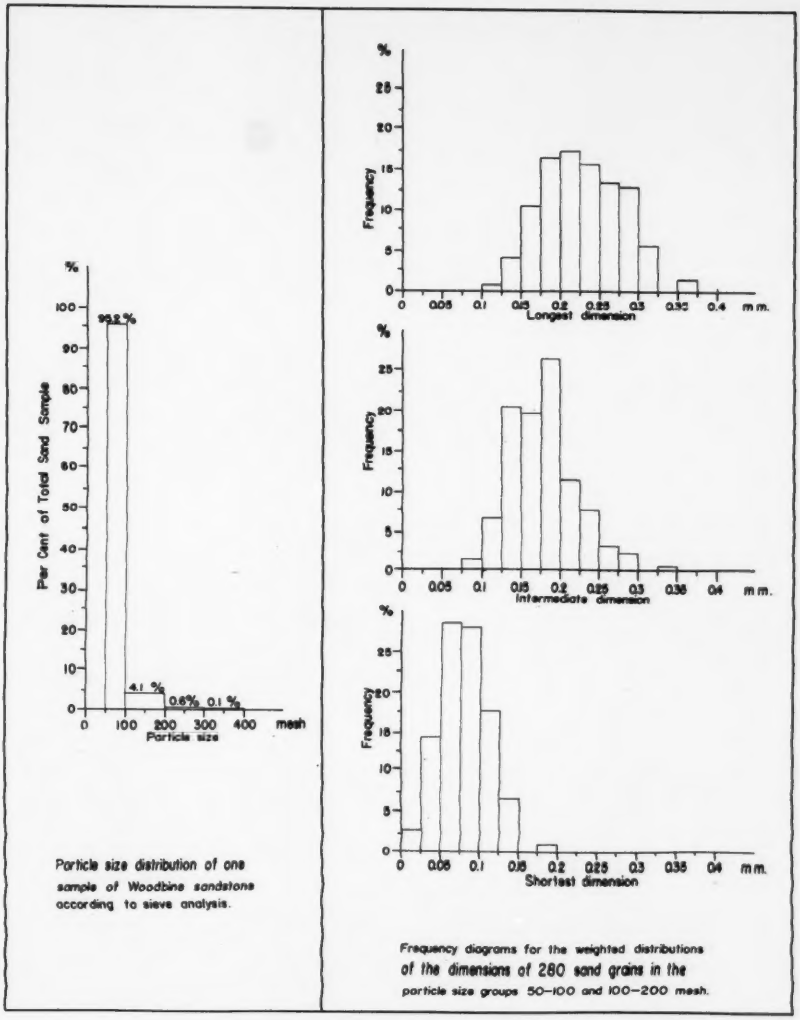
%
Per Cent of Total Sand Sample
95.2 %
4.1 %
0.6%
0.1 %
Particle size
mesh
Particle size distribution of one sample of Woodbine sandstone according to sieve analysis.
Frequency
Longest dimension
Intermediate dimension
Shortest dimension
mm.
Frequency diagrams for the weighted distributions of the dimensions of 280 sand grains in the particle size groups 50–100 and 100–200 mesh.

FIG. 5.—Particle characteristics of a sample of Woodbine sandstone.

b. determining the sphericity ψ' and the shape factor F for the parameters from the sphericity chart,

c. compiling and evaluating the results for the total sample or portions of it.

The distributions of the longest, intermediate and shortest dimension of the component particles of the sediment sampled may be obtained more or less as a by-product of the shape analysis.

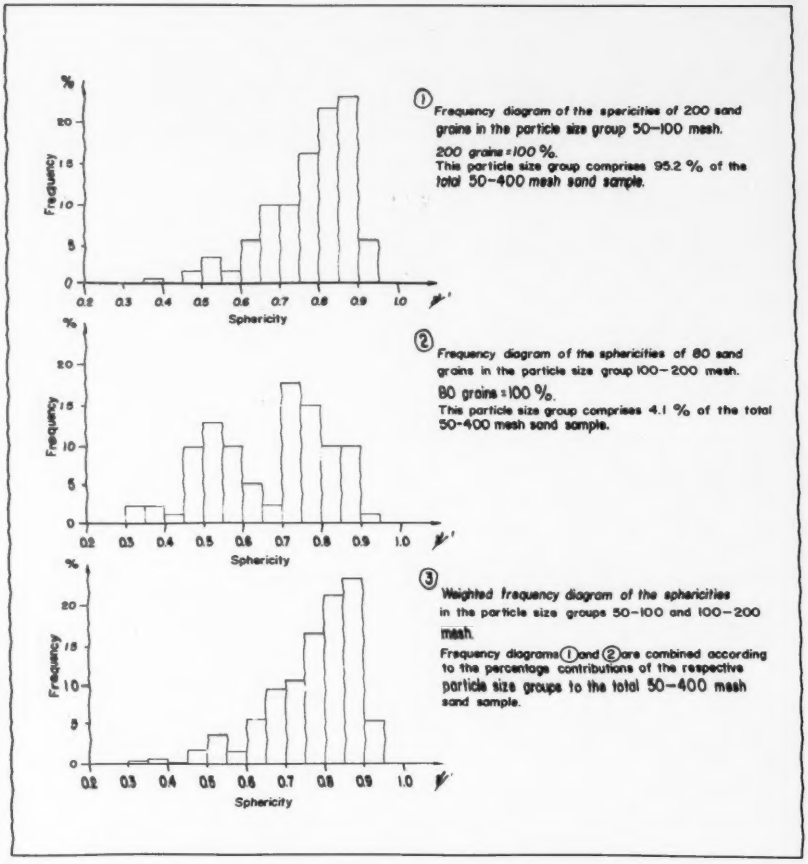
%
Frequency
Sphericity
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
① Frequency diagram of the sphericities of 200 sand grains in the particle size group 50–100 mesh.
200 grains = 100 %.
This particle size group comprises 95.2 % of the total 50–400 mesh sand sample.
② Frequency diagram of the sphericities of 80 sand grains in the particle size group 100–200 mesh.
80 grains = 100 %.
This particle size group comprises 4.1 % of the total 50–400 mesh sand sample.
③ Weighted frequency diagram of the sphericities in the particle size groups 50–100 and 100–200 mesh.
Frequency diagrams ① and ② are combined according to the percentage contributions of the respective particle size groups to the total 50–400 mesh sand sample.

FIG. 6.—Frequency diagrams for the distribution of ψ'.

APPLICATION OF THE METHOD

Procedure

In order to demonstrate the application of the method described, a sample of Woodbine sandstone was obtained from an outcrop near Arlington, Tarrant County, Texas. About 1½ lbs., disaggregated by soaking and gently agitating in water, was separated into four particle size groups by wet sieving. The limits of these groups were 50–100, 100–200, 200–300, and 300–400 mesh. Particles which passed 400 mesh were discarded. Figure 5 shows the particle size distribution of the sand sample. A photogrammetric method was used for the tridimensional measurement of the sand grains. ψ' and F were determined for 280 grains and the results are presented in a series of frequency diagrams (figs. 6 and 7). The distributions of the three mutually perpendicular grain dimensions were obtained as a by-product of the shape analysis (fig. 5).

Results

In order to evaluate the data, fractile diagrams for the weighted distributions of ψ' and F were prepared on both arithmetic and logarithmic probability scales (figs. 8 and 9). It can be seen from these graphs that both distributions approximate a straight line more closely when plotted on the logarithmic probability scale, i.e. the distributions are more nearly log-normal than normal in their character. Since ψ' and F are not distributed normally, the mode is used rather than the arithmetic mean as an indication of the central tendencies of the shape characteristics. For the sphericity ψ' of this particular sample of Woodbine sandstone

$$0.85 < \text{mode} < 0.90$$

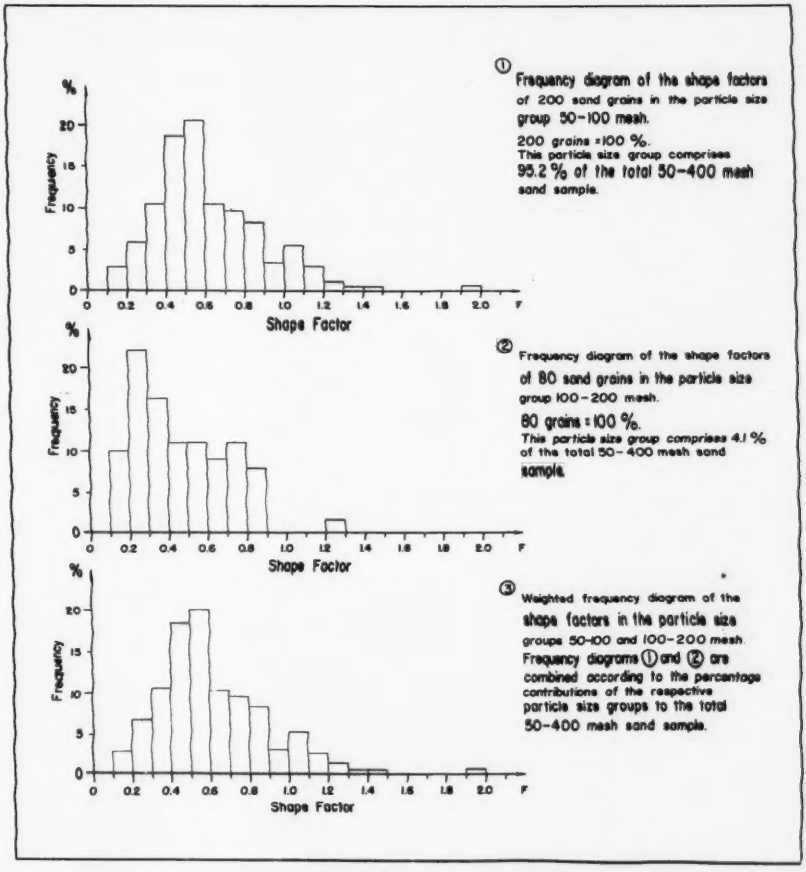
① Frequency diagram of the shape factors of 200 sand grains in the particle size group 50-100 mesh.
200 grains =100 %.
This particle size group comprises 95.2 % of the total 50-400 mesh sand sample.
② Frequency diagram of the shape factors of 80 sand grains in the particle size group 100-200 mesh.
80 grains = 100 %.
This particle size group comprises 4.1 % of the total 50-400 mesh sand sample.
③ Weighted frequency diagram of the shape factors in the particle size groups 50-100 and 100-200 mesh.
Frequency diagrams ① and ② are combined according to the percentage contributions of the respective particle size groups to the total 50-400 mesh sand sample.
%
Frequency
Shape Factor
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 F

FIG. 7.—Frequency diagrams for the distribution of F.

and for the shape factor F

$$0.50 < \text{mode} < 0.60.$$

Both distributions are somewhat bimodal with relatively insignificant but recognizable secondary modes as follows:

sphericity ψ'

$$0.50 < \text{secondary mode} < 0.55$$

shape factor F

$$1.0 < \text{secondary mode} < 1.1.$$

SUMMARY

A method for the tridimensional shape analysis of sedimentary particles has been described. Its main features are:

a. the measurement of three mutually perpendicular grain dimensions,

b. the approximation of the irregularly shaped sedimentary particle by a tetrakaidekahedron which is defined by the dimensions measured,

c. the quantitative expression of the shape of the particle simultaneously in terms of Zingg's shape factor and an approximation of Wadell's true sphericity.

It was shown that the use of the approximating formula seems to be justified for both rounded and angular forms and that the expression constitutes an improvement over expressions based on the operational definition of sphericity.

The applicability of the method was demonstrated by the analysis of the component grains of a sample of Woodbine sandstone.

It is thought that this method for expressing particle sphericity may become a useful tool in various phases of stratigraphy.

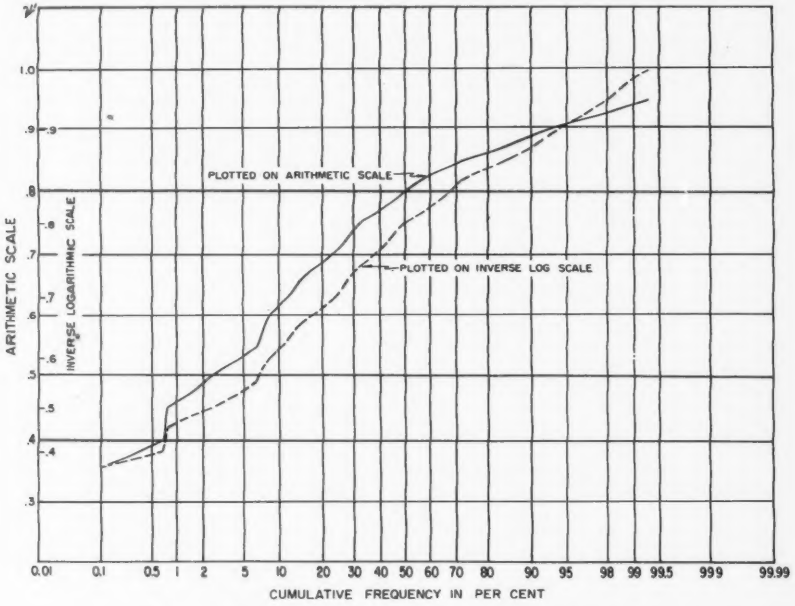

FIG. 8.—Fractile diagram for the weighted distribution of ψ'.

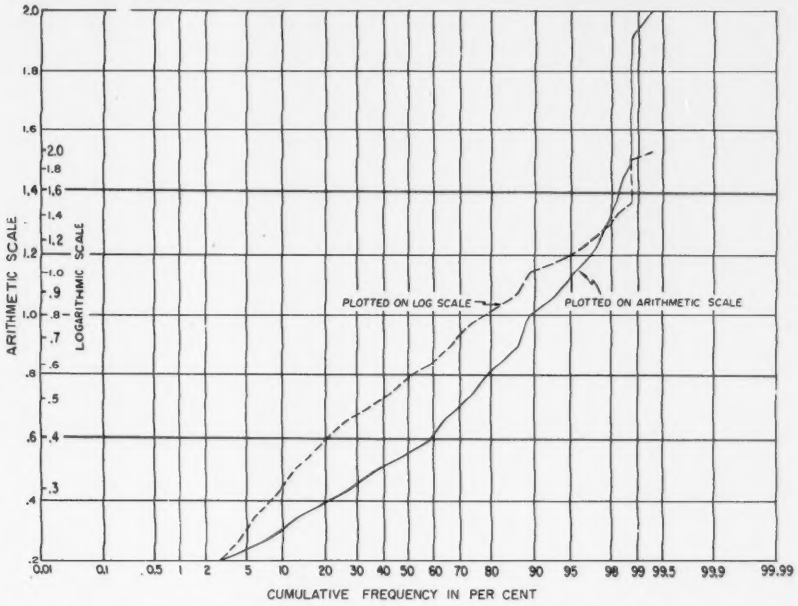

FIG. 9.—Fractile diagram for the weighted distribution of *F*.

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APPENDIX

I. *Surface Area of the Tetrakaidekahedron with the Half-Axes a, b, and c*

a) Surface area of three pairs of equal and opposite quadrilateral faces:

$$1)\ 2 \cdot c \frac{b}{2} = bc$$

$$2)\ 2 \cdot b \frac{a}{2} = ab$$

$$3)\ 2 \cdot c \frac{a}{2} = ac.$$

Area of six quadrilateral faces = 1) + 2) + 3) = $ab + bc + ca$.

b) Surface area of four pairs of equal and opposite hexagonal faces:

There are eight hexagons each consisting of six equal triangles. The sides of each triangle expressed in terms of the half-axes a, b, and c are

$A=\frac{1}{2}\sqrt{a^2+b^2}$; $B=\frac{1}{2}\sqrt{a^2+c^2}$; $C=\frac{1}{2}\sqrt{b^2+c^2}$.

By definition the surface area of a plane oblique triangle is

$$S=\sqrt{s(s-A)(s-B)(s-C)}$$

where $s=\frac{1}{2}(A+B+C)$.

Substituting $\frac{1}{2}(A+B+C)$ for s, $\frac{1}{2}\sqrt{a^2+b^2}$ for A,

$\frac{1}{2}\sqrt{a^2+c^2}$ for B, and $\frac{1}{2}\sqrt{b^2+c^2}$ for C

the following expression for the surface area of one triangle is obtained

$$S=\tfrac{1}{8}\sqrt{a^2b^2+b^2c^2+c^2a^2}$$

and therefore the area of one hexagon

$$=\tfrac{3}{8}\sqrt{a^2b^2+b^2c^2+c^2a^2}.$$

Hence the area of eight hexagonal faces

$$=6\sqrt{a^2b^2+b^2c^2+c^2a^2}.$$

c) Total surface area of the tetrakaidekahedron:

This is equal to the sum of the areas of six quadrilateral and eight hexagonal facets which is

$$S_T=ab+bc+ac+6\sqrt{a^2b^2+b^2c^2+a^2c^2}.$$

II. Volume of the Tetrakaidekahedron with the Half-Axes a, b, and c

The volume of the tetrakaidekahedron is equal to the volume of an octahedron with the half-axes $\frac{3}{2}a$, $\frac{3}{2}b$, and $\frac{3}{2}c$ minus those portions which are truncated by a cube with the half-axes a, b, and c.
Hence

$$V_T=\frac{9}{2}abc-\frac{2}{3}\left(\frac{abc}{4}+\frac{bca}{4}+\frac{acb}{4}\right)$$
$$=\frac{9}{2}abc-\frac{3}{6}abc=\frac{8}{2}abc=4\,abc.$$

III. Expression for an Approximation of the Degree of True Sphericity

By definition $p=c/b$, $q=b/a$.

Substituting p for c/b and q for b/a, the expression for the surface area of the tetrakaidekahedron becomes

$$S_T=\frac{b^2}{q}\left[1+p(1+q)+6\sqrt{1+p^2(1+q^2)}\right]$$

and the expression for the volume becomes

$$V_T=4b^3\frac{p}{q}.$$

Let r be the radius of the sphere of equal volume, then

$$4b^3\frac{p}{q}=\frac{4}{3}\pi r^3$$

and solving for r

$$r=b\sqrt[3]{\frac{3p}{\pi q}}.$$

Let S_S be the surface area of the sphere of the same volume as the tetrakaidekahedron, then

$$S_S=4\pi r^2$$

and substituting $b\sqrt[3]{3p/\pi q}$ for r

$$S_S=4b^2\sqrt[3]{9\pi\frac{p^2}{q^2}}.$$

The degree of true sphericity if approximated by

$$\psi'_S=\frac{S_S}{S_T}$$

$$=\frac{4b^2\sqrt[3]{9\pi\frac{p^2}{q^2}}}{\frac{b^2}{q}\left[1+p(1+q)+6\sqrt{1+p^2(1+q^2)}\right]}.$$

This reduces to

$$\psi'_S=\frac{12.2\sqrt[3]{p^2q}}{1+p(1+q)+6\sqrt{1+p^2(1+q^2)}}.$$

IV. Expression for an Approximation of the Degree of True Sphericity if the Surface Area of the Orthotetrakaidekahedron of Equal Volume is Substituted for S_S

The orthotetrakaidekahedron of the same volume as the tetrakaidekahedron has three equal half-axes, namely $\sqrt[3]{abc}$. Therefore $p=1$ and $q=1$, and the surface area of the orthotetrakaidekahedron becomes

$$S_{OT}=13.4(\sqrt[3]{abc})^2.$$

Substituting b/q for a and bp for c

$$S_{OT}=13.4b^2\left(\frac{p}{q}\right)^{2/3}.$$

The degree of true sphericity is approximated by

$$\psi'_T=\frac{S_{OT}}{S_T}=\frac{13.4b^2\left(\frac{p}{q}\right)^{2/3}}{\frac{b^2}{q}\left[1+p(1+q)+6\sqrt{1+p^2(1+q^2)}\right]}.$$

This reduces to

$$\psi'_T=\frac{13.4\sqrt[3]{p^2q}}{1+p(1+q)+6\sqrt{1+p^2(1+q^2)}}.$$

V. Expression for an Approximation of the True Degree of Sphericity using a Triaxial Ellipsoid as the Approximating Body

Legendre's formula for the surface area of a triaxial ellipsoid is

$$S_E=2\pi\left\{c^2+\frac{ab}{\sin\gamma}\left[\sin^2\gamma E(\gamma,K)+\cos^2\gamma F(\gamma,K)\right]\right\}$$

where $\gamma=\cos^{-1}c/a$

$$K=\frac{a}{b}\sqrt{\frac{b^2-c^2}{a^2-c^2}}$$

E and F = elliptic integrals of the first and second kind

a, b, and c = half-axes of the ellipsoid, $a\geqq b\geqq c$.

Substituting p for c/b and q for b/a Legendre's formula becomes

$$S_E=2\pi\left\{p^2+\frac{1}{q\sin\gamma}\left[\sin^2\gamma E(\gamma,K)+\cos^2\gamma F(\gamma,K)\right]\right\}$$

where $\gamma=\cos^{-1}pq$

$$K=\sqrt{\frac{1-p^2}{1-p^2q^2}}.$$

The volume of the triaxial ellipsoid is

$$V_E=\frac{4}{3}\pi abc=\frac{4}{3}\pi\frac{p}{q}.$$

The radius of the sphere of equal volume is $\sqrt[3]{p/q}$ and the surface area of this sphere is

$$S_S=4\pi\left(\frac{p}{q}\right)^{2/3}.$$

The degree of true sphericity is approximated by

$$\psi'_E=\frac{S_S}{S_E}=\frac{4\pi\left(\frac{p}{q}\right)^{2/3}}{2\left\{p^2+\frac{1}{q\sin\gamma}\left[\sin^2\gamma E(\gamma,K)+\cos^2\gamma F(\gamma,K)\right]\right\}}$$

which reduces to

$$\psi'_E=\frac{2\left(\frac{p}{q}\right)^{2/3}}{p^2+\frac{1}{q\sin\gamma}\left[\sin^2\gamma E(\gamma,K)+\cos^2\gamma F(\gamma,K)\right]}.$$

VI. Expression for Krumbein's Operational Sphericity if a Tetrakaidekahedron is Substituted for the Triaxial Ellipsoid

Based on the operational definition of sphericity Krumbein (1941) developed the expression

$$\psi_{OPK}=\sqrt[3]{\frac{bc}{a^2}}=\sqrt[3]{q^2p}$$

where a, b, and c = half-axes of an ellipsoid

$$p=\frac{c}{b}$$

$$q=\frac{b}{a}.$$

Substituting a tetrakaidekahedron for the ellipsoid the expression becomes

$$\psi_{OPKT}=\sqrt[3]{\frac{4abc}{\frac{4}{3}\pi r_{CS}^3}}=\sqrt[3]{\frac{3}{\pi}}\cdot\sqrt[3]{\frac{abc}{r_{CS}^3}}$$

where

a, b, and c = half-axes of a tetrakaidekahedron

r_{CS} = radius of the circumscribing sphere.

$$r_{CS}=\sqrt{a^2+\left(\frac{b}{2}\right)^2}=\frac{a}{2}\sqrt{4+\frac{b^2}{a^2}}=\frac{a}{2}\sqrt{4+q^2}$$

Hence

$$\psi_{OPKT}=\sqrt[3]{\frac{3}{\pi}}\sqrt[3]{\frac{8bc}{a^2(\sqrt{4+q^2})^3}}$$

$$=\sqrt[3]{\frac{3}{\pi}}\cdot\frac{2}{\sqrt{4+q^2}}\cdot\sqrt[3]{\frac{bc}{a^2}}$$

$$=\sqrt[3]{\frac{3}{\pi}}\cdot\frac{2}{\sqrt{4+q^2}}\cdot\psi_{OPK}.$$

Obtaining numerical values for various values of q and substituting 0.9847 for $\sqrt[3]{3/\pi}$ the following table is compiled:

q	$\frac{2}{\sqrt{4+q^2}}$	$\sqrt[3]{\frac{3}{\pi}}\cdot\frac{2}{\sqrt{4+q^2}}$	*Deviation from Mean*
1	0.895	0.880	−6.0%
0.8	0.928	0.914	−2.4%
0.6	0.958	0.943	+0.7%
0.4	0.980	0.964	+3.0%
0.2	0.994	0.978	+4.5%
		mean 0.936	

Hence $\psi_{OPKT}=(0.936\pm0.056)\psi_{OPK}$

VII. Comparison of ψ'_E with ψ' for Four Triaxial Ellipsoids and Fifteen Ellipsoids of Rotation

The table below shows a compilation of the results:

p	q	F	ψ'_E	ψ'	% Error
0.1	1.0	0.1	0.419	0.380	−9.3
0.2	1.0	0.2	0.625	0.573	−8.3
0.33	1.0	0.33	0.80	0.75	−6.3
0.4	1.0	0.4	0.851	0.799	−6.1
0.5	0.2	2.5	0.603	0.565	−6.3
0.5	0.4	1.25	0.745	0.697	−6.4
0.5	0.6	0.833	0.829	0.777	−6.3
0.5	0.8	0.625	0.880	0.829	−5.8
0.5	1.0	0.5	0.910	0.862	−5.5
0.6	1.0	0.6	0.950	0.907	−4.5
0.8	1.0	0.8	0.989	0.947	−4.2
1.0	1.0	1.0	1.000	0.955	−4.5
1.0	0.1	10.0	0.588	0.561	−4.6
1.0	0.2	5.0	0.732	0.695	−5.1
1.0	0.33	3.0	0.85	0.81	−4.7
1.0	0.4	2.5	0.885	0.841	−5.0
1.0	0.5	2.0	0.93	0.883	−5.0
1.0	0.6	1.67	0.959	0.915	−5.0
1.0	0.8	1.25	0.993	0.948	−4.5

Root-mean-square error	5.8%
Maximum error	−9.3%
Minimum error	−4.2%

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FIGS. 1–8, MARCH, 1956

MOTTLED CARBONATE ROCKS IN THE MIDDLE DEVONIAN OF EASTERN NEVADA

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ABSTRACT

Three types of mottling are conspicuous in the dolomites and limestones of the Simonson formation, middle Devonian age of eastern Nevada. Petrographic and chemical studies combined with field observations indicate probable origins of these types. A review of other reports of mottled carbonate rocks indicates the existence of several additional types of mottling. Each type is the result of variations of the processes which cause the segregation of the component minerals. These processes may differ during deposition of the sediments or at any later time.

A genetic classification is proposed which may be useful for interpreting the depositional environment and diagenetic history of the various types of mottled carbonates. The major groups of the classification are: organic control, depositional control, intrastratal deformational control, diagenetic control, and depositional and diagenetic control.

INTRODUCTION

Mottling is a common characteristic of carbonate rocks and indicates their history. A spotty or patchy color pattern referred to as mottling is created by the presence of a contrasting matrix and enclosed bodies. In his monograph on carbonate rocks, Cayeux (1935, p. 180) refers to mottling as "Un des exemples les plus connus se rattache aux phénomènes de dolomitisation."

Conspicuously mottled carbonate strata form a persistent zone in the Simonson dolomite of Middle Devonian age in eastern Nevada (Osmond, 1954, p. 1931). The Upper Ordovician through Middle Devonian section is about 3000 feet of dolomite overlain by Upper Deovnian limestone. The mottled strata in the Simonson are most prominent 200 to 400 feet below the limestone.

This paper presents a résumé of previous references to mottling, a detailed description of mottling in the Simonson dolomite, and conclusions as to the significance of mottling.

PREVIOUS REFERENCES TO MOTTLING

In his classic work on dolomites, Van Tuyl (1914, p. 345) summarizes his investigations of mottling as follows: "All cases of mottling examined seem best explained on the assumption that the magnesia was introduced from without and that the mottling resulted from the selective replacement of fucoids in the one case and from the spreading out of the alteration from certain favorable centers in the rock in the other."

Van Tuyl (1914) cites the following points of evidence for this statement: (1) the existence of unaltered fucoid markings containing less than two percent $MgCO_3$ in association with dolomitic ones, (2) association of both types of mottling with dolomite seams and other evidence of imperfect dolomitization, (3) gradation of mottled beds into beds which are uniformly dolomitic both laterally and vertically, and (4) existence of gradational series between limestone showing incipient mottling and true dolomite.

Sixteen examples of mottled limestone are described in this reference. These range in age from Ordovician to Mississippian and are exposed at localities in Iowa, Missouri, Illinois, Pennsylvania, New York, and Vermont.

From these descriptions the following points can be made: the dolomite is usually lighter colored and coarser crystalline than the limestone it is replacing. A reversal of this crystal size relationship is reported in the Chazy limestone on

Valcour Island. This might be explained by a slight dolomitization of the mottles. The process of dolomitization can be stopped during any stage in the development of a completely dolomite rock. In all the instances mentioned the organization of the mottles is related to stratification.

The Ordovician mottled limestones of Manitoba have been described and discussed by Wallace (1913) and Birse (1928). The outstanding feature of these rocks is the dark-colored anastomosing dolomitic tubes in the light-gray limestone matrix. These tubes, of organic origin, extend through the strata and caused localization of the dolomitization.

Mottling in the Platteville limestone (Middle Ordovician) at Minneapolis-St. Paul was described by Griffin (1942), and from a similar stratigraphic position in Clayton County, Iowa, by Leonard (1905, p. 260). Griffin suggests that the limestone was originally a fossiliferous calcareous ooze with finely divided siliceous shale partings. He attributes the mottled pattern to the partings which acted as channels for the migration of dolomitizing concentrated connate brines. These fluids were concentrated by evaporation and caused to migrate by compaction.

Agnew (personal communication, 1952) attributes the mottling observed in the carbonate rocks of the Wisconsin lead-zinc district to dolomitization or silicification localized by nuclei such as pyrites, quartz grains, and argillaceous streaks.

Canadian limestones of New York (Fisher, 1954) exhibit mottling as the result of reticular distribution of buff-weathering dolomite in a white-weathering dark aphanic limestone. Fisher (1954, p. 271) suggests "that seaweeds supplied adequate magnesium to the lithotope to effect local dolomitization, which gave rise to fucoidal dolomites and mottled limestones."

Similar mottling is present in the Garden City limestone (Lower Ordovician) of northern Utah and in the El Paso limestone (Lower Ordovician) in southeastern Arizona. This type of mottling is developed on bedding surfaces and is accentuated by weathering.

In the Bonneterre formation (Cambrian) of southeastern Missouri, John S. Brown (personal communication, 1954) describes irregular shaped bodies of dark very fine-grained limestone in light-gray limestone or shaley limestone which is larger grained than the mottles. He believes the dark areas may represent flocculated masses of argillaceous lime muds, because in the lower part of the formation the mottles are tinted red by the inclusion of particles derived from the red shales in the base of the formation. It is interesting that dolomitization is not selective and the whole mottled unit is usually affected to the same degree.

Mottled limestone is so abundant and distinctive in the Muav limestone (Cambrian) of the Grand Canyon region that McKee (1945, pp. 71–76) has referred it to a special facies representing the seaward part of each member of the formation. The matrix is a dull-gray, aphanic limestone mottled with yellow or red-brown blotches of calcareous siltstone in forms ranging from tube-like to globular (strato-cumulus). The siltstone is believed to have filled shrinkage cracks and cavities formed by solution and organic processes in the lithified calcareous ooze. These mottles may be dolomitic in a limestone matrix; also, in some places the matrix is dolomitized.

Mottling is a characteristic feature of the Cambrian limestones of the Cordilleran miogeosyncline. The black aphanic limestone is interlaminated with gray-weathering very fine crystalline dolomite, argillaceous dolomite, or dolomitic limestone. The laminae are usually about ½ inch thick and have very uneven surfaces. These surfaces sometimes touch or come close together at intervals of a few inches, and mottles of the gray laminae are enclosed in black limestone. The mottles are very irregular in shape but are elongate in the plane of the lami-

nation. This type of mottling seems to be the result of deposition of alternating sediments which were deformed on a laminar scale during deposition or early in lithification.

Hewett (1931) mentioned mottling in the lower half of the Goodsprings formation (Middle Cambrian) near Goodsprings, Nevada. He described the rocks as containing elongate light-gray areas with transitional borders in a dark-gray or nearly black matrix; sometimes the colors are reversed. The light-gray material is dolomite, and the dark-gray is more calcitic. Hewett concluded that the distribution of lime and magnesia must have been accomplished during or shortly after deposition, since the mottled strata persist in the midst of homogeneous strata.

Not far from Goodsprings, McAllister (1952, p. 13) recognized mottling in the Ely Springs dolomite (Upper Ordovician) of the Panamint Range, California. This mottling is described as being somewhat lighter in the dark beds and darker in the light beds. Of importance is the fact that in some places the mottling is parallel to the bedding and so close in some layers that it produces the effect of wavy bands. McAllister also reported mottling in the Hidden Valley dolomite (Silurian and Lower Devonian) and in the Lost Burro formation (Middle [?] and Upper Devonian). The latter is described as mottled by spaghetti-like forms, attributed to cladoporoids.

"Mackerel dolomite" in the lower part of the Nevada formation (Middle Devonian) of the Ruby Mountains, Nevada, is described and illustrated by Sharp (1942, p. 662; pl. 3, fig. 1). This unit contains irregular, curving, oblong bodies of white crystalline dolomite in a matrix of dark dolomite. The white bodies are $\frac{1}{4}$ to $\frac{1}{2}$ inch thick and one to several inches long. Some of them have fine-grained cream-colored cores of limey dolomite. Figure 7 is a photograph of a specimen collected at this locality.

The Simonson dolomite (Middle Devonian) was named by Nolan (1935, p. 19) from exposures in the Deep Creek Mountains southwest of Gold Hill, Utah. The mottled beds in this section lack the textures of and are thicker than the associated beds which were deposited very slowly in shallower water. Nolan attributes the dolomite beds with limestone mottles to subsidence having exceeded deposition.

Beales (1953) discusses dolomitic mottling in Devonian limestone in the Canadian Rockies of western Alberta. The mottling of these limestones is of two types: one shows control by primary features such as bedding, laminae, "worm" tubes, or "algae"; and the other results from dolomitization progressing irregularly through the rock. In the first case the margins of the mottles are sharp, while in the second case they are diffuse. In this mottling the slightly coarser dolomitic mottles are usually darker on weathered surfaces than the enclosing limestone.

The evidence of conditions of deposition of the mottled limestone includes (Beales, 1953, pp. 2286–2287): very uniform fine-grained deposits of wide extent, no evidence of shallow water deposition, macrofossils relatively uncommon for a shelf limestone, remains of pelagic life, abundant algae, and small amount of fine-grained insoluble residue. These are believed to indicate steady subsidence with accumulation of organic calcareous muds.

Some varieties of pseudobreccia referred to by European writers seem to have characteristics in common with mottling. In his comprehensive study of limestones and dolomite, Cayeux (1935, pp. 178–182) discusses two types of pseudobreccia. The first type results from a differentiation, in place of very fine calcite, originally homogeneous. This material is subjected to recrystallization progressing outward from a multitude of centers within the deposit. Recrystallization is not complete, and bodies of the original limestone are left to develop the

breccia appearance. The margins of the remnants are both sharp and transitional.

The second type of pseudobreccia has an epigenetic origin and is caused by metasomatism failing to reach completion in a given stratigraphic unit. Cayeux mentions a sequence grading from those cases in which the metasomatism is arrested at its beginning, giving rise to irregular nuclei enclosed in a matrix of original limestone, to the cases of advanced metasomatism in which the vestiges of the original material are irregular, subangular to angular in form.

Grumeleuse structure (Cayeux, 1935, p. 271) in carbonate rocks is characterized under the microscope by the presence of a multitude of elements resembling the form of dark clots having gradational contacts with a clear matrix. These dark areas average .05 mm in diameter, and in stages of development they show phases from a cloudy rock to the formation of clots with increasing density of color and sharpness of margin.

Cayeux discusses this structure (or texture) as being of secondary origin and also of detrital origin. The secondary origin is pertinent to the present discussion. This type of grumeleuse structure is referred to the same process responsible for pseudobreccia and pseudoolithic structures. The original homogeneous limestone mud begins to crystallize throughout its mass, the progress of the phenomenon is such that it gradually isolates some portions of the mud, either as microscopic grumeaux (clots), pseudoolites, or large pseudobreccia "fragments." Cayeux states that to his knowledge grumeleuse limestones of secondary origin are always poor in detrital (insoluble) material, rarely contain organic remains, and usually form in rock with cryptocrystalline texture.

Hatch, Rastall, and Black (1938, pp. 192–193) state that "certain dolomites show a peculiar patchy or mottled appearance, which is often accentuated by weathering." They pass on to a discussion of the pseudobreccias of South Wales which owe their appearance entirely to an early partial recrystallization, followed by selective dolomitization. The dolomitic material is lighter colored than the angular or irregular limestone bodies it encloses. The dolomitization is believed to have affected unrecrystallized limestone and not recrystallized nodular bodies.

Hatch et al. also write that "most mottled limestones and dolomites which have been described from North America appear to differ from dolomitized pseudobreccias both in their structure and in their origin." The writer, however, believes that there is a similarity between pseudobreccias and mottled carbonate rocks.

Wood (1941, pp. 195–197) discussed grumeleuse structure under the English term "clotted." He stated that there is no definite boundary between clotted limestone and pseudobreccia. The "fragments" are dark, more translucent, recrystallized parts of the rock. He suggested that bodies of aragonite would become stabilized by recrystallization; following this the calcite matrix would be more susceptible to changes due to its smaller crystal size.

A distinctly different type of mottling is found in the Cambrian of southeastern Arizona and the Pennsylvanian of central New Mexico and southeastern Arizona. In these cases the black aphanic limestone remnants are lenticular, discoidal and coalescing in a black aphanic siliceous limestone matrix which weathers rust-brown. This type of mottling is conspicuous on weathered surfaces and appears to be caused by widespread reorganization of silica in an argillaceous limestone. Concretionary bodies of purer limestone developed with argillaceous material concentrated between them. Contemporaneous or subsequent silicification accentuated the pattern.

Extreme cases of mottling are developed within a few tens of yards of some igneous intrusions. This has happened to the thin-laminated argillaceous limestones in the Amole formation (Lower

Cretaceous) in the Tucson Mountains, Arizona, and the Pogonip limestone (Lower Ordovician) at Mount Hamilton, Nevada. These strata have been partially or entirely silicated and then mottled by the growth of euhedral epidote crystals along the lamination planes and random cross-cutting planes.

In evaporite sequences, aphanic primary dolomite may contain irregular, *lenticular mottles of anhydrite. This* relationship occurs in the Permian of West Texas *and the Devonian of southern* Utah. These mottles may represent "boudinage" remnants of thin anhydrite laminae in the dolomite. Compacting forces have caused the anhydrite to flow unevenly into small bodies separated along the lamination planes by areas where the anhydrite has been removed by the squeezing.

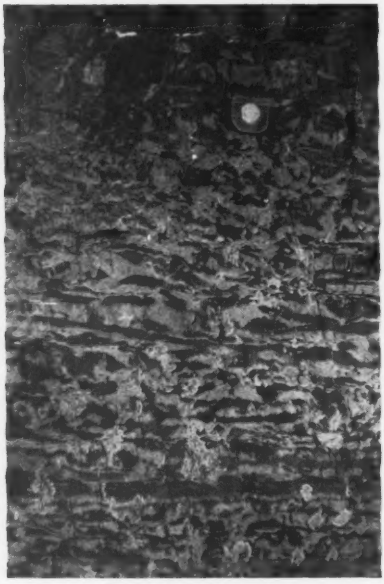

FIG. 1.—Typical mottled dolomite of "even-laminated" type from Simonson dolomite in Schell Creek Range, Nevada. Case for tape is two inches along top.

Also, primary salt blebs create a *mottled appearance in laminated shales* and fragmental dolomites in the West Texas Permian (Schwade, 1947). A similar relationship, on a larger scale, is developed by crystal aggregates of complex carbonate salts in the lacustrine dolomites and siliceous dolomites of the Green River and Uinta formation in the Tertiary of Utah (Hunt, et al., 1954, p. *1676). These bodies of salts,* enclosed in carbonate rocks, probably formed as pri*mary constituents of the sediments in the* saline environments. Thus, mottling can *be created by primary variations in the* distribution of chemical and clastic sediments.

DESCRIPTION OF SIMONSON MOTTLED ROCKS

The mottled carbonate rocks investigated by this writer seem comparable with some of those described in the literature; however, such descriptions are subject to different interpretations. *Three types of mottling* are developed in the Simonson dolomite. Lamination, in*trastratal deformation, and indeterminate* "centers" situated at random *through the rock are the controlling fac*tors.

Mottling is restricted to definite strata and does not cross stratification planes (fig. 1), although it *may grade upward* into homogeneous unmottled dolomite. Mottled strata averaging *three feet in* thickness are present at all exposures throughout an area 200 miles from north to south and 80 miles from east to west (fig. 2). The lowest occurrence of mottling varies from 26 to 197 feet above the next underlying stratigraphic marker. The occurrence is systematically higher to the east (rises 200 feet in 100 miles) which indicates a closer relationship to the eastward transgression of facies than to the subsidence of basins in the miogeosyncline (Osmond, 1954, p. 1931). Above the lowest mottled stratum there may be a few or several mottled strata interspersed through the overlying few tens of feet of

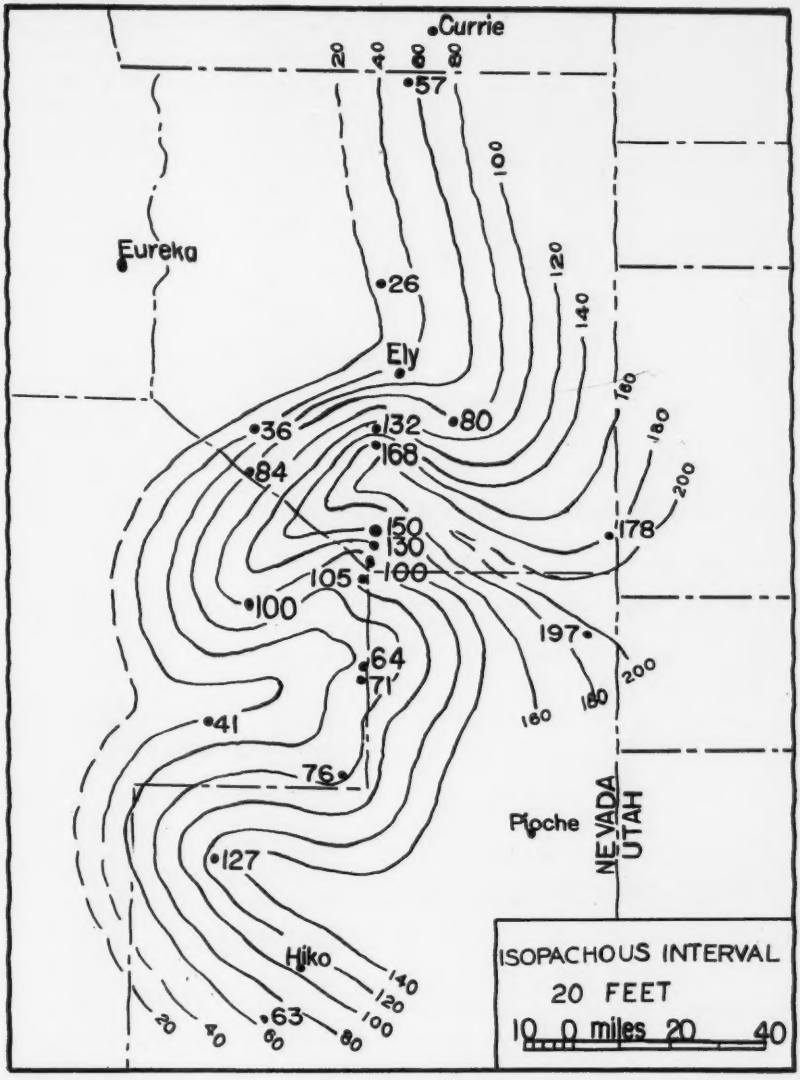

FIG. 2.—Isopachous map of interval between lowest mottled strata and next lower stratigraphic marker in the Simonson dolomite. The mottling rises to the east and may be time transgressive facies.

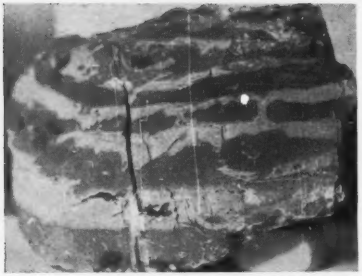

FIG. 3.—"Even-laminated" mottling, specimen is entirely dolomite with the darker vestiges of laminae being more calcareous and having more bitumen and larger crystal size than the lighter colored dolomite (×½).

dolomitic rocks. The mottling in the upper part becomes increasingly less distinct, and the uppermost extent is difficult to determine.

The first type of mottling in the Simonson is developed in uncontorted, laminated carbonate rock and is referred to as the "even-laminated" variety (fig. 3). The second type is seen in highly contorted laminated carbonate rock and is called the "roiled" variety (fig. 7). A third variety is developed in unlaminated very fine crystalline fragmental limestones (fig. 8). In this "permeative" variety dolomitization progresses outward from many centers and produces very irregular mottles with gradational margins.

In all the varieties two types of rock are present, a light-colored dolomite and a dark-colored limestone. Depending on the stage of mottling, either rock may form the mottles in a matrix of the other rock. Sometimes the dark-colored rock is dolomite; if so, it is more calcareous than the light.

In the case of calcitic mottles, the dolomite matrix is fine crystalline in contrast to the aphanic calcite. Whereas, if the mottles have been dolomitized, the crystals developed are larger than those of the fine crystalline dolomite matrix.

In the "even-laminated" variety the light-colored fine crystalline dolomite developed along interlaminar planes and also along more widely spaced planes which cut across one or more laminae (fig. 5). This results in the apparent isolation of tabular mottles of the original limestone laminae. A sequence is established from laminated limestone to rock in which interlaminar dolomite isolates limestone remnants (figs. 4, 5) to rock in which the remnants have been subsequently dolomitized (fig. 3).

Later the remnants of the original limestone may be dolomitized but with a different texture than the first stage. The "second" stage appears to follow an interruption in the process, because, if the first stage had gone to completion, an unmottled dolomite strata would result.

The dolomitization of the matrix determines the shape of the mottles. When it is more extensive, the volume of the mottles is small and, depending on the homogeneity of the sediment, produces a greater or lesser resemblance to vestiges of laminae. Tabular form is lost in the presence of abundant cross-cutting planes. The development of concavities (caries) in the host rock also destroys tabular form (fig. 4).

FIG. 4.—"Even-laminated" mottling in which the primary structure (lamination) has been almost obscured. The black mottles are aphanic limestone in lighter colored dolomite. The margins are entrenched because of solution and loosening in zone of mineral mixture (×½).

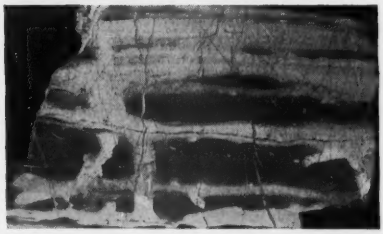

FIG. 5.—Mottled black aphanic limestone with interlaminar and cross-cutting planes of fine crystalline light colored dolomite (×1). Note calcite-filled fractures which developed subsequent to the partial dolomitization. Mottles have both sharp and intermixed contacts and are relatively free of dolomite euhedra. This rock grades laterally into laminated limestone and has been changed by dolomitization to the stages of figure 4 and figure 3.

The three dimensional relationships of even-laminated mottling were determined by comparing eleven sections through a representative specimen. The sections were taken at quarter-inch intervals and the outlines of the mottles were drawn on tracing paper. It was found that the mottles are not isolated bodies but are flat with very irregular plan and many arm-like extensions. Also, in many places the mottles are separated from ones above by only an interlaminar surface of interrupted deposition. In these cases, the light colored dolomite is not present along the interlaminar planes.

The roiled type of mottling (fig. 7) is the result of two factors. These are: alternating laminae of two varieties of carbonate sediment with contrasting colors and intrastratal soft-rock deformation referred to as roiling. These factors combine to create an intermingling of irregular bodies of the two types of sediment. In the cases studied these are both dolomite. This type of dolomite has been called "mackerel dolomite" by Sharp (1942, p. 662).

Within these mottles are traces of bent and broken fine laminae, which provide evidence of the original nature of the deposit. The lower contact of the mottled zone in figure 7 is a slippage surface, and the material below is more intensely roiled than that above. However, the mottling is not obvious below because of the lack of contrasting constituents and the very intensive roiling.

The light colored dolomite lam'nae involved in this type of mottling are quite similar to strata in the Simonson which exhibit profuse evidence of plastic deformation. It seems logical to assume these laminae were similarly plastic when deformed. The dark dolomite is quite similar to strata which characteristically are even-laminated and show evidence of hardening early in their history. The dark laminae in figure 6 seem to have been deposited unevenly between more plastic laminae, and this rock represents the condition of the sediments in figure 7 before they were roiled.

The third type of mottling (fig. 8) exhibits variable response to the texture and structures of the rock. Some of the small fragments are uneffected by dolomitization, others are replaced, and others are partially replaced. The overall shape of the mottles is much more irregular, and the margins are typically more transitional than in the other two types. This type is formed by dolomitization permeating outward from random centers through the rock. This process ceased before the rock was completely dolomitized.

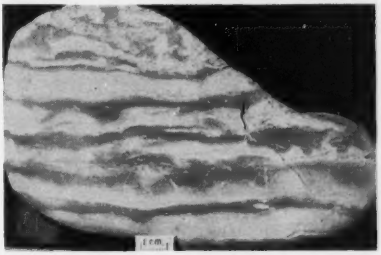

FIG. 6.—Alternating light and dark dolomite laminae with uneven surfaces. The lighter colored material reacted plastically while the darker laminae were being deposited. This type of rock is the predecessor of the roiled mottled rocks (fig. 7).

SUMMARY

The development of the mottled pattern is the result of incomplete or differential dolomitization which may follow a pattern established at the time of deposition.

The importance of lamination, a primary structure, and the lack of importance of subsequent structures, such as some fractures, indicate an early date of dolomitization. Also, the evidence that dolomitization preceded plastic dislocations indicates that it took place before the sediment was lithified. The different result of the "second" stage of dolomitization may be explained as post-lithification, when channels were restricted and some magnesium was derived from the matrix.

Mottling seems to be related to rate of burial and concomitant expulsion of connate fluids. Slow burial would allow sufficient time for complete dolomitization, but more rapid burial would cause fluids to migrate and the channels to close before consummation of the limestone strata. Mottled strata do not necessarily occur as a transition between limestone and dolomite beds.

The occurrence of mottled strata has environmental significance which can be interpreted in the light of regional relationships. Tentatively, mottling is attributed to semi-restricted shelf environments in which a fine textured calcareous sediment containing organic residues is buried at a moderate rate.

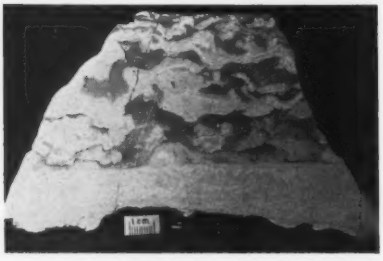

FIG. 7.—Roiled mottled dolomite caused by deformation of alternating light and dark laminae (fig. 6). The lower part of the specimen is intensely deformed and is separated from the mottled zone by a plane of slippage. This is identical to the "mackerel dolomite" of Sharp (1942).

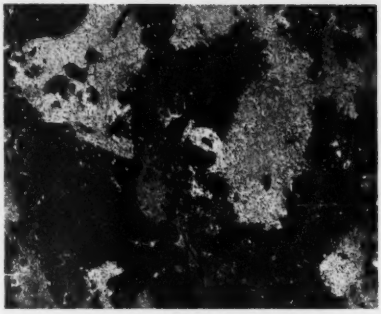

FIG. 8.—Permeative mottling formed by dolomitization (dolomite is lighter colored) progressing outward through fragmental limestone (black). The process is partially controlled by fragments in this unlaminated rock (×7).

Proposed Classification

Mottled carbonate rocks are an easily recognizable rock type that may be significant in interpreting the history of the deposits. There are several kinds of mottled carbonate rocks, each indicative of a slightly different history.

Because this is a common and widespread phenomenon many lithologic descriptions include the term "mottled." However, unless additional information is provided the significance of the mottling cannot be determined, and the full value of the description is not realized.

The types of mottling discussed in this paper can be placed in the following classification. The groups are based on types of primary control of the pattern. Comparison of the characteristics of these types with other occurrences should prove useful in (1) noting similarities, (2) establishing additional types, and (3) increasing the evidence of the environments indicated by the types.

I. Organic Control
   a. Tubular
   b. Fucoidal (reticular)
   c. Corals (Cladopora) and Bryozoa (Thamnopora); Spaghetti Rock
   d. Burrow Filling
   e. "Algal"
   f. "Worm tubes"

II. Depositional Control
   a. Shrinkage cracks
   b. Solution-hole filling
   c. Evaporite blebs (precipitated crystal aggregates)
   d. Flocculated masses

III. Intrastratal Deformational Control
   a. Roiled ("mackerel rock")
   b. Uneven lamination
   c. Anhydrite augen

IV. Depositional and Diagenetic Control
   a. Laminae relics

V. Diagenetic Control
   a. Permeative (spreading loci)
   b. Pseudobreccia; Grumeleuse (clotted)
   c. Concretionary (lenticular)
   d. Metamorphic

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FIGS. 1–3, MARCH, 1956

GRAPHIC AIDS IN STUDY OF STRATA[1]

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ABSTRACT

Experiments with several vocabularic and graphic techniques involving pre-field organization have led to a final hinged-card field log which is plotted directly in the field as measurement, collection, and field description of the stratigraphic section proceed. This graphic field log can be at any scale consistent with good sedimentologic sampling, but should contain spaces for the entry of all subsequent laboratory data. Upon completion of field and laboratory work, this dual log may be used for direct plotting on tracing cloth, or may be reduced by photostat for the construction of cross sections.

INTRODUCTION

Geologists have long utilized the field note book and the planimetric or topographic map in recording all field observations. In basic geologic mapping, the measurement of stratigraphic sections may be considered secondary to the mapping of contacts and geologic structure. For the sedimentologist, however, spatial location, important as it is, is secondary to careful measurement, field description, and collection of typical samples from outcrop sections. The purpose of this paper is to illustrate a graphic form which is considered to be far better than the ordinary field note book in the rapid and adequate field description of stratigraphic sections. The writer recognizes that he will invade the last great personal stronghold of the geologist; i.e., how to arrange his field notes so that a maximum amount of data is gathered in a minimum of time. Without a complete analysis of mechanical aids, abbreviations, lithologic symbolism, and techniques of measurements or sample collection, the summary here presented is an elemental one of graphics which might guide the student of sedimentology to a more rapid field technique and lead to a technique which involves no replotting of field data during completion of the laboratory work.

[1] Presented before the Society of Economic Paleontologists and Mineralogists, March 27, 1952, Los Angeles, California.

IDEAL TECHNIQUE

After recognition of the problem, choice of the region whose sedimentologic history is to be studied, reading of all background materials, and assembly of previously published maps, sections, and stratigraphic descriptions, the sedimentologist should study air photographs to plot logical distribution, density, and accessiblity of the outcrops to be measured and described. Study of each section can be facilitated greatly by graphic forms easily handled in the field and on which all field data can be plotted. Immediate collation of samples and sample interval measured and described must be possible, yet the field log should be so complete that fault-repeated sections, gaps, and field correlations can be recognized as the work advances. The ideal technique, then, is one in which such elusive parameters as color, sorting, texture, matrix composition, chert description, and positive fossil identification can simply be added to the completed field log so that replotting of field data is unnecessary during laboratory examination.

Despite the fact that the end point of field or laboratory work is not the log itself, the theory of the geogram as elucidated by Marr (1924), and the technique of collection as outlined by Otto (1938) should be kept in mind. The desired end result, via correlated lithologic cross sections, lithofacies-isolith-isopleth maps,

and schematic environmental reconstruction, is to discover the sedimentational and tectonic history of a region (Krumbein, 1952, p. 200). Although it must be remembered that the field work should be entirely complete, any time saved in grubbing for data in the hills is additional time that can be utilized in appraising basic data to arrive at the truth.

DESCRIPTIVE TECHNIQUES

Written Description

Complete work descriptions of strata may be made at the fancy of the investigator, or may follow a schedule of observations such as that devised by Goldman and Hewitt (Krumbein and Pettijohn, 1938, pp. 8–10). A simple lined, tabular form is used by many field men. At best, such written descriptions, with or without simple graphic additions in the field, are difficult and time consuming to transcribe in preparation for laboratory work, and usually result in omission of pertinent field data necessary to the sedimentologist.

Verbal Check-list Description

Simple printed forms can be devised so that a single sheet is utilized for each sample interval. Presumably the field investigator bases his sample interval on some logical lithologic subdivision such as Otto's "sedimentational unit."

Despite the fact that these forms are vast improvements in field notation, these data must be transcribed completely into a log system in the laboratory prior to detailed lithologic work. A second detrimental factor is the bulk of the paper that must be carried in the field in order to measure just one complex section.

Graphic Check-list Description

Graphic check-lists have been devised leading to completeness in stratigraphic descriptions rarely utilized by field investigators. Generally they are vast improvements over the simple verbal check-list forms since any number of lentils can be recorded on one sheet of paper if size of the sheet is no consideration. Reduced to a printed form in a loose-leaf field book, a graphic check-list technique could prove useful to most sedimentologists; however, the data must be transcribed into log form manually. Although such transcription can be done by non-geologists, there are numerous opportunities for error. Another detrimental factor is the lack of proportions for the lentils, resulting in a serious lack of opportunity for graphic correlations with other field sections measured utilizing the same system.

Graphic-Spatial Description

Scaled thickness for measured sections recorded in a bound geologic notebook results in graphic portrayal of lithology as determined in the field and records the type and position of the sample collected. Word descriptions are used with appropriate lithologic symbols and abbreviations.

This system of field notes was utilized in a study of the Fernvale and Viola limestones (Wengerd, 1948), but it was found that transcription of data to hinged-card strip logs was tedious and overly time-consuming. Transcription was necessary in order to compare the field data with similar logs devised for the study of well cuttings and cores. Approximate correlation could be done in the field by doubling the field notebook pages of later sections foward to previously logged sections; however, only the left hand pages of the notbook could be used for the graphic log. In general, the bound nature of the field book plus the necessity for complete transcription to a scaled log were deciding factors in abandonment of this field procedure.

Loose-leaf forms, devised for use on a clipboard during the Paradox-Hermosa study in 1951 (Wengerd and Strickland, 1954), provide a quick means of taping pages together for field correlations. However, complete replotting of field data is necessary before lithologic study can be done in the laboratory.

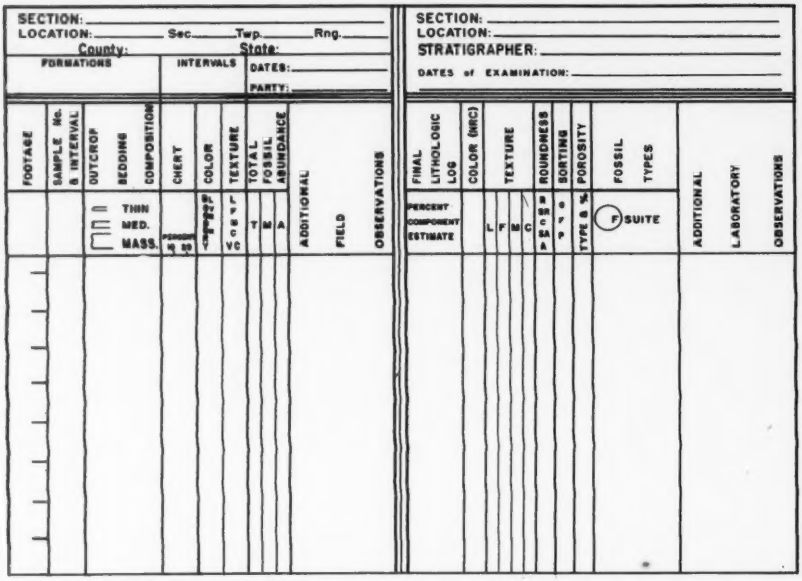

FIG. 1.—A final graphic-spatial field log on the left, with the laboratory log of the same scale on the right (reduced).

A hinged-card log was devised which could be made up prior to field work and on which one could record the following data: footage, chert, sample number and interval, color, texture, outcrop form, beddedness, composition, fossil abundance and types, and other field observations. Immediately after field work each day, these cards could be hinged with opaque scotch tape and utilized for correlation with previously measured sections. Attempts were then made to enter laboratory data on the field form in red ink, with particular emphasis on porosity, chert type, color under blue incandescent or fluorescent light, final textural analysis, added observations on composition, and laboratory identification of fossils. It is needless to do more than mention that this final log was so cluttered that more time was spent differentiating the symbology than in carrying forward correlations or in the computation of lithofacies components. Although the form led to strict analysis of the outcrop section, replotting of all field data was necessary onto a laboratory log whose main emphasis was on laboratory observation.

Final Field-Laboratory Log

Because of variations in scale on field logs employed by sedimentologists working different types of sections, uses to which the final logs will be put, or plain personal differences, it is recognized that no truly final field-laboratory log system can be devised to fit all situations. Nevertheless, whether the field scale is 1 inch to 5 feet, 10 feet, 20 feet, or 50 feet, if time of transcription is to be saved, the field and laboratory logs must be the same scale. The length of section measured, finiteness of stratigraphic detail, and amount of lithologic detail will always control this scale choice, but the

writer found the scale of 1 inch to 20 feet wholly practical, utilizing hinged logs to represent stratigraphic sections as thick as 1000 feet.

The attempt to combine on one form card all the columns necessary for the entry of all field and laboratory data led to three major difficulties: (1) the card was too wide for a clip board which could fit into a field notebook case; (2) if the clip board was carried in the open, one hand was lost for climbing (a factor the flat-lander would not consider in measuring sections along road cuts); (3) the columns into which laboratory data were to be entered became inordinately smudged and scarred during field work.

Figure 1 shows a graphic-spatial field card *on the left*, which makes up into a final hinged field log for preliminary correlations. This card is a 7 inch × 10½ inch form, or can be photographically rescaled to approximately 5 inch × 8 inch size, printed on heavy filing-card stock, with one heading card per stratigraphic section and the remainder of the log made up of cardstock forms lined as shown on the bottom part of the left half of figure 1. Utilizing the same scale, a heading card was devised, similar to the right half of figure 1. On this half, all laboratory data are entered after the field work is completed.

Upon completion of the full study of a stratigraphic section, the field log and laboratory log are taped together lengthwise. A third, narrow, laboratory-entry log could also be designed on which to record heavy mineral and insoluble residue data.

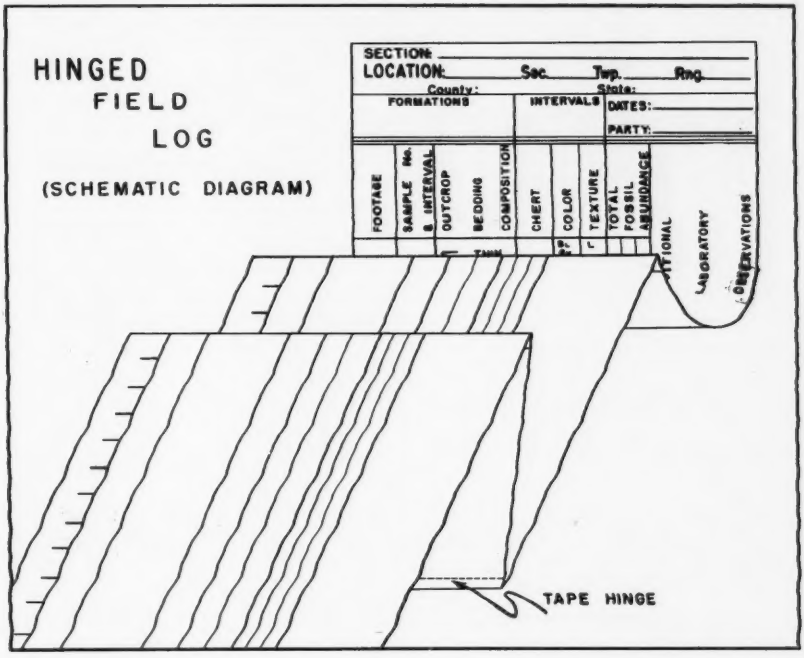

FIG. 2.—The hinged field log. Scale is fore-shortened in this diagram to show two folds or hinges.

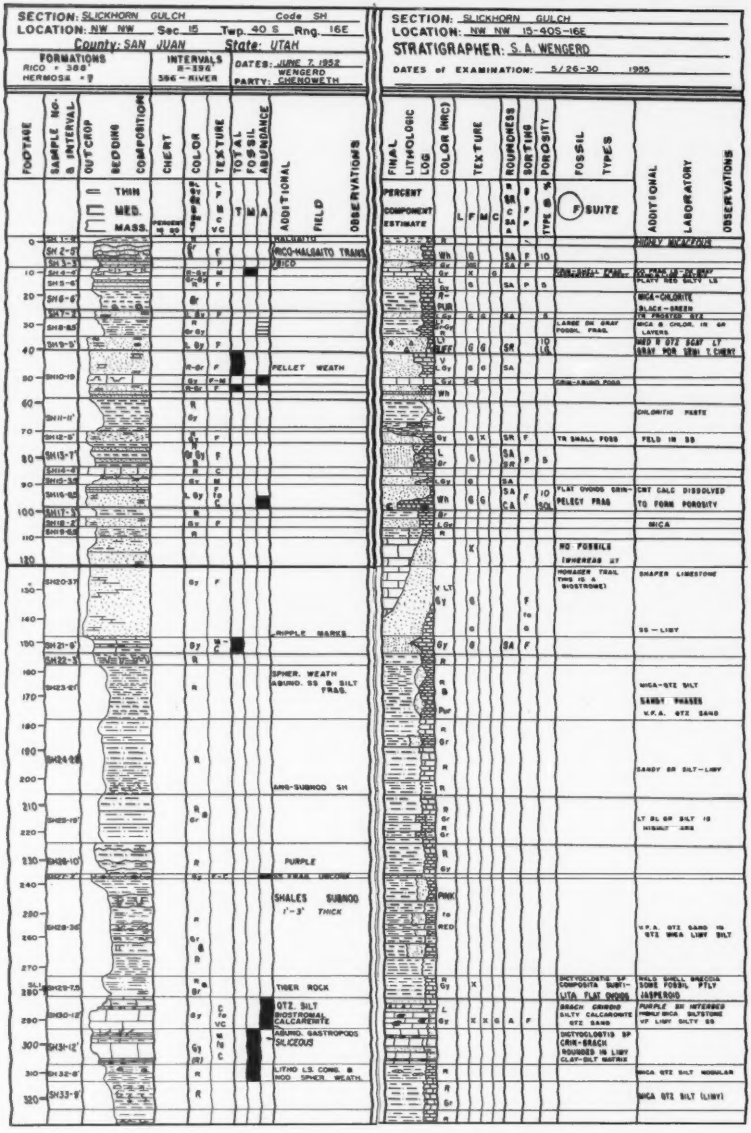

FIG. 3.—Part of a completed field-laboratory log of the Slickhorn Section, San Juan County, Utah (reduced).

The final result is a hinged log (fig. 2) which appears bulky, but all the data are horizontally coincident at the same scale and the log can be compared with similar logs simply by unfolding the hinged sections in which correlations or lithofacies and stratal variations are sought. Figure 3 shows the upper part of such a completed log with all field and laboratory data entered thereon.

REPRODUCTION

The recording of field data on unhinged cards carried on a small clip board is done with a 4H pencil, and data from later laboratory examination are similarly entered. A heavy, white card stock is virtually necessary since erasures are made in the field and laboratory. Gaps in the section are recorded to scale if the interval can be measured. Overlaps of section are readily detected directly in the field. In any case, the hinged card can be cut or a new section can be added in multiples of lesser amount than the length of one card. Both these conditions require one intermediate fold which is not difficult to handle.

After all field and laboratory work is done, the entire combination log is inked with india ink, without any transcription of data, and the whole log is photostated or photographed to a reduced scale of 1 inch to 50 feet. The log may be taken apart at certain lengths for mounting on the photo-copying board. The reduced copies are then cut apart and hinged again to form a complete log for each section studies.

Because the sedimentologist is so often limited by the 42-inch-width of tracing cloth, and finally by the 7×9 inch printed page and the simple infolds allowed in publications, these photographic reductions result in loss of some important detail. In drafting from these reduced logs, such detail must be left out, for further reduction in publication will certainly result in their illegibility.

Cross-section drafting on tracing cloth can be done directly over the light table utilizing these photographically reduced logs at which time the finest detail must be omitted in lithologic-stratigraphic cross sections; however, the original logs are splendid for the computation of lithofacies components and the direct comparison of logs in appraising important stratal variations.

Since the research sedimentologist is most often interested in working 1 to 5 formations ranging from 50 to 1000 feet in thickness, this system is most useful for developing lithofacies variation maps, which can be published at small scales and supplemented by schematic stratal-variation cross sections.

CONCLUSIONS

A summary of written, check-list, graphic, and combination logs prepared in the field as measurement and collection of stratigraphic section proceed suggests that the ideal field log is one which:

1. can be easily handled in the field and will fit into the field kit on a clip board;
2. is graphic and to a scale which will allow direct comparison to other measured sections in the field;
3. can be hinged so that any length of log can be opened for inspection to determine gaps and overlaps of measured section;
4. can be taped to a laboratory log for direct comparison as the laboratory log is prepared;
5. can be reproduced economically without transcription of field data;
6. can be redrafted to any smaller scale, after photographic reduction, by the overlay method utilizing tracing cloth over a light table.

It is recognized that every sedimentologist has personal preferences as to scale, data to be recorded, graphic rendition of final results, and interpretation of final results; however, any technique which speeds up the process to its final conclusions yet loses few of the vital facts must be considered an advance in field and laboratory procedure.

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FIGS. 1–8, MARCH, 1956

A USE OF ROUNDNESS TO DETERMINE DEPOSITIONAL ENVIRONMENTS[1]

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ABSTRACT

More than 200 sand samples have been analyzed for roundness values, using roundness as curvature or roughness of surface. These have shown a consistent difference between beach and dune roundness for the same area. Because the roundness value changes at the boundary between the beach and the dunes, the difference appears to be due to selective sorting by the wind. Application of the roundness characteristic has been made to a series of borings in the barrier islands along the Texas and Louisiana coasts as an aid in determining which of the sand formations represent dunes. Dune material has been found in scattered samples from these borings down to depths of 44 feet. A series of samples taken from so-called "beach ridges" of the Texas coast have also been analyzed for roundness and have been found to represent dune sands, showing they are eolian rather than water-laid, although their linearity suggests dunes inside of a prograding shoreline.

INTRODUCTION

Roundness is a confusing term since it may refer to a surface or an outline. In relation to sand grains the curvature or roughness of the surfaces are important since they may determine the environment of deposition or the distance of transportation. Unfortunately, curvature of surfaces of small grains can not be measured conveniently although estimates can be made under the binocular microscope. Many people have recognized that roundness in the sense used here is an important characteristic of sand sediments in relation to their environments of deposition. Several articles have mentioned the greater roundness of dune than of water-laid sands[2] (see for example Russell, 1939, and Pettijohn, 1949). For the most part, this greater rounding has been ascribed to abrasion during wind transportation. For reasons presented later in this paper, the writers believe that selective sorting during transportation has caused the greater roundness of the dune sands (see Pettijohn and Lundahl, 1943). Several methods have been suggested for measuring roundness, but to date few workers have made use of roundness measurements to determine the environments in which old sediments were deposited.

In the course of extensive sampling in two Gulf Coast areas, the central Texas coast and the east Mississippi Delta, numerous sand samples have been collected. This has afforded an opportunity to determine the relationship of roundness values to environments of deposition. To check the results of the study in the Gulf Coast area, samples of beaches and adjacent dunes have been obtained from several other areas. Having found that a measurable and consistent difference exists between beach and dune roundness in all areas investigated, this information has been used as an aid in determining the depositional environments of some unknown sand deposits found in borings at various depths up to

[1] Contribution from the Scripps Institution of Oceanography, New Series No. 849. This investigation was supported by a grant from the American Petroleum Institute, Project 51.

[2] The contention by Mattox (1955) that wind tends to select grains of low sphericity does not necessarily disagree since his few measurements were based on a ratio of inscribed and circumscribed circles on a grain outline (Riley, 1941), and therefore gave no information on roundness in the sense of curvature of surface. For example, he would have given a high sphericity value to a six-sided flake of mica, although the true sphericity and roundness would be very low.

60 feet in the central Texas coast and from Breton Island, Louisiana. Roundness studies have also been applied to determine the origin of so-called "beach-ridges" on the barrier islands of the Texas area.

All roundness determinations in this work were made by Beal. A study of field relations was made by Shepard. Appreciation is expressed to D. G. Moore and J. R. Curray who collected many of the samples used in the study, and to J. R. Moriarty who prepared the illustrations.

METHODS OF STUDY

The $\frac{1}{8}$ to $\frac{1}{16}$ mm sieving from each of the samples was put through an Otto microsplit until only a few hundred grains remained. These were sprinkled on a black counting tray and the tray tapped lightly to orient the grains on their flattest faces. To assure randomness, traverses were made across the tray and every quartz grain entering the field of view of the microscope was classified until approximately 100 grains had been examined. Roundness values obtained for the individual grains were then averaged to obtain a value for the sample. For reasons presented below, Powers' (1953) roundness scale was used in this study.

CHOICE OF A ROUNDNESS SCALE

The work of Sorby (1880) first indicated that "shape" is a measurable parameter of sand-sized particles. In his studies he kept separate the concepts of sphericity and roundness although it remained for Wadell (1932, 1933, 1935) to define these terms in a quantitative way. Wadell's roundness formula is based on the average radius of the corners and edges of the particle compared to the radius of the maximum inscribed circle when projected to a "standard size" of 70 mm. Because of the time required to arrive at a roundness value by Wadell's method, it is not a practical method for use in any study involving large numbers of samples. His roundness formula, however, serves as a basis for the later visual comparison charts discussed below.

Krumbein (1941) published a visual comparison chart for use with pebbles. This chart is drawn from pebbles whose roundness had been determined by Wadell's method. His silhouettes are arranged arithmetically with roundness values ranging from 0.1 to 0.9. Krumbein states that the chart can be used for rapid visual estimations of sand grains under the binocular microscope if it is suitably reduced in size.

Powers (1953) published a comparison chart using photographs of clay models representing six roundness classes. Each class is represented by two models with the same roundness value; one for grains of relatively high sphericity and the other for grains of relatively low sphericity (fig. 1). He has divided his scale into class intervals arranged geometrically to

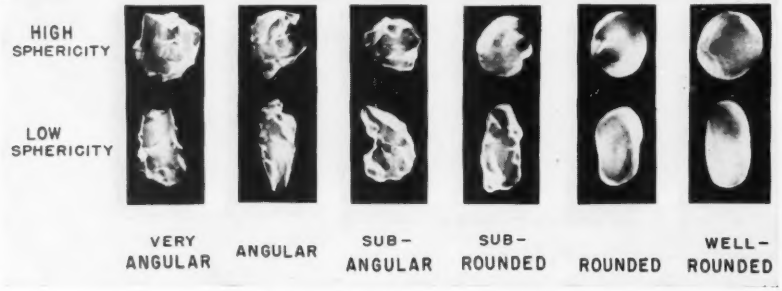

FIG. 1.—Powers' scale of roundness (1953).

provide larger divisions in the higher (more rounded) end of the scale.

Each of the two scales was considered for use in the present study. Whereas both scales are based on the Wadell method, roundness estimations made using either of the scales should give results comparable to the other. Therefore, it was felt that the selection of one of the two scales should be governed primarily by the ease with which the operator could make comparisons between the scale and the quartz particles in the field of view of the microscope. Making a selection on this basis, we felt that the Powers' roundness scale had several advantages over Krumbein's chart.

The first 16 samples of the present study were worked using Powers' method. The operator then attempted to re-work a number of the samples using the Krumbein scale. After having made estimations using the Powers' scale, which closely resembles actual quartz grains as seen under the microscope, the operator experienced difficulty in comparing the quartz particles with the silhouettes of Krumbein's scale. Possibly the difficulty was the result of using Powers' method first, thereby allowing the operator to become accustomed to the photographs used as references in that scale.

Because of the difficulty experienced in using Krumbein's scale for direct comparison of the quartz grains and silhouettes, we decided to reproduce images of the quartz grains from three of the samples as silhouettes which could then be compared with Krumbein's scale. Approximately 100 quartz grains of each sample were photographed with a Polaroid "picture in a minute" camera. The outline of each grain was then carefully traced on the photograph using a crowquill pen and India ink and the photographic image bleached away. The outlines of the grains were then filled in and the resulting silhouettes compared with a copy of Krumbein's chart which had been reduced to give image sizes as small as those obtained by the technique mentioned above.

Table I shows average roundness values for three samples from Matagorda Island in the central Texas area as determined by the Powers' method and the technique described in the preceding paragraph (Krumbein's scale).

TABLE I

	Dune	Beach Berm	Beach at Water's Edge
Powers' scale	.42	.34	.33
Krumbein's scale	.51	.37	.37

In each case the roundness value computed using Krumbein's scale was higher than the determination made with Powers' scale, and the difference between the beach and dune samples was more pronounced. As mentioned previously, both scales are based on the method of Wadell and should yield comparable results. In any study depending upon visual comparisons, the "human element" is difficult to evaluate. It is possible that the operator reacts differently to the photographs of Powers' scale than he does when using the silhouettes of Krumbein. Another possibility is that in tracing the outlines of the grains on the photographs used in the measurements by Krumbein's scale, the operator inadvertently smoothed out some of the smaller corners and raised the roundness values. In any case, the values obtained by the two methods are reasonably close and the same dune-beach roundness relationship was found.

One of our reasons for the choice of Powers' scale now appears to have been fallacious. Pettijohn (1949) pointed out that, " . . . the eye can readily distinguish slight differences in roundness when the roundness values are low, but cannot make such distinctions when the values are large." Powers accepted this as fact and arranged his geometric scale to give

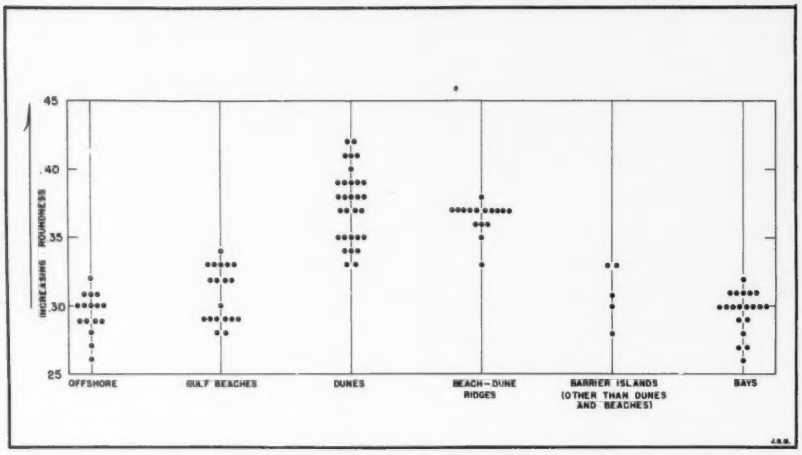

FIG. 2.—Roundness values of surface samples from sandy environments of the central Texas coastal area. For location of this area see figure 6.

larger divisions of the higher roundness values. In selecting a scale for use in the present study, the operator felt that this arrangement of the class limits offered a definite advantage over the arithmetic scale of Krumbein. However, use of Powers' scale for estimation of roundness of over 200 samples has convinced the operator that he can more easily distinguish differences in roundness when the roundness values are high. The statistical study of Rosenfeld and Griffiths (1953) published after the present study was started shows the same result; that it is easier to detect small differences in the roundness of well-rounded grains than in more angular grains. The operator now feels that in any future study, a roundness scale giving finer divisions in the higher roundness values would be desirable.

CRITICAL TESTS OF RESULTS

More than 100 samples whose origin was unknown to the operator were used for roundness measurements in this study. Nearly one-half of the roundness values shown in figure 2 and the samples from the lagoon of the Rio San Miguel, Baja California, shown in figure 3 were obtained by working with the unknown samples. This has given us confidence that the differences in roundness between dunes and adjacent beaches found in this study, though small, are real differences in the sediments and not merely a reflection of psychological "bias" on the part of the operator.

The samples were taken as they became available from the sediment laboratory after mechanical analyses had been completed, and in no case was an attempt made to work on several dune samples followed by several beach samples.

As an additional check on the validity of the roundness difference, we decided to have another operator re-work three samples to see if the dune, beach, and "beach-dune" ridge[3] roundness relationships found by Beal would be confirmed. One sample each of a dune, a beach, and a "beach-dune" ridge was micro-split, labeled with meaningless sample numbers, and given to J. R. Curray for roundness determinations by the Powers'

[3] So-called since origin was uncertain.

method. Table II gives the roundness values for these three samples as determined by both operators. While the values obtained by Curray are lower in all three cases than those obtained by Beal, the relationship between the beach, dune, and "beach-dune" ridge roundness values are the same.

TABLE II

	Beal	Curray
Beach sample	0.31	0.29
Dune sample	0.36	0.33
"Beach-dune" ridge	0.37	0.35

ROUNDNESS RELATED TO GRAIN SIZE

We decided to use quartz particles in the sievings between $\frac{1}{8}$ and $\frac{1}{16}$ mm throughout our study for the following reasons:

1. Sands of this size are common in all of the samples from every environment in the central Texas coastal area.
2. By concentrating our efforts on one

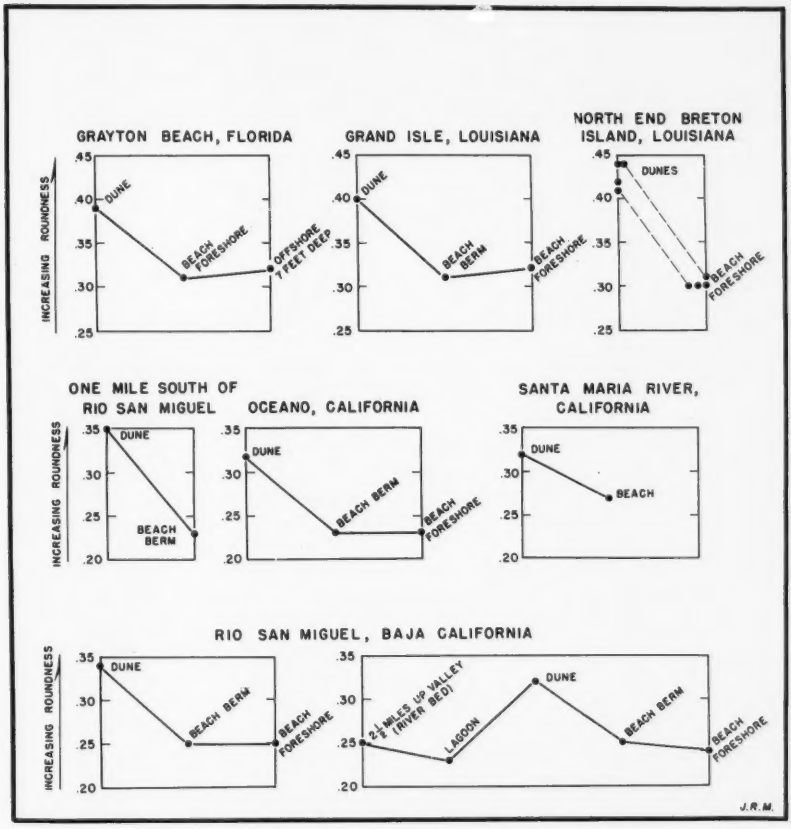

FIG. 3.—Roundness values for dune and beach surface samples from various areas other than the central Texas coast.

size fraction we were able to make roundness determinations on many more samples than would otherwise have been possible.

3. The dune and beach sands which represent most of the samples have almost identical size frequency percentages of $\frac{1}{8}$ to $\frac{1}{16}$ mm grains (Shepard and Moore, 1955, fig. 28).

Since roundness can vary with size, our choice of one sieving for study led us to investigate the size distribution of the sands within the $\frac{1}{8}$ to $\frac{1}{16}$ mm of dunes and beaches. This was accomplished by taking splits of dune and beach sands from Matagorda and St. Joseph Islands in the central Texas area and measuring diameters perpendicular to the long axis of 100 grains from each sample with a microscope equipped with a micrometer ocular. All of the techniques of eliminating "bias" used in the roundness measurements were also applied to this study. The measurements were plotted as cumulative curves of the size distribution and compared. We then looked for a difference in the size distribution that could explain the difference in roundness found in this study. Since the size distribution is the same, we feel that the difference in roundness cannot be a result of concentration in the dunes of the larger sand sizes within the $\frac{1}{8}$ to $\frac{1}{16}$ mm sievings.

COLLECTION OF FIELD SAMPLES

Although some sands for roundness measurements were obtained from the bays and the open Gulf of the areas studied, the great majority came from the barrier islands, particularly from the beaches and from the dunes. In sampling, care was taken not to collect any special concentrate represented by unusual conditions. In general the samples were taken from the top two inches of the beach or dune surface. However, in order to determine whether the tops of the dunes were different from the sand at some little distance below the surface, a series of samples was taken at a variety of depths. No consistent difference in roundness was found as a result of this check.

Because it has been commonly assumed that the sand in the dunes is rounded by abrasion, samples were collected at the outer margin of the dune directly at the contact with the beach sand. Other dune samples were taken at various distances up to three miles in from the beach source. On one occasion samples were obtained during a hurricane tide which had produced a flooding of the waters over some of the very low dunes on the upper beach, so that an opportunity was found to check the effects of a double environmental influence.

ROUNDNESS OF SURFACE SEDIMENTS

Of the 200 samples for which an average roundness value has been obtained, the majority came from beaches and dunes of St. Joseph, Matagorda, Mustang, and northern Padre islands. The roundness value of each of the samples in this central Texas area is plotted against environment in figure 2. In addition to beach and dune sands, a few sand samples were examined from the shallow open Gulf and from portions of the bays near the margins of the islands, along with a few samples from the flats on the inside of the barrier islands. It will be noted that the roundness of the dunes is quite regularly greater than in any of the other environments.

The distinction in this central Texas coastal area between the beaches and the dunes is duplicated by every other area from which we have samples (fig. 3). It will be noted, however, that the roundness on some west coast dunes is as low as in the beaches along the Gulf coast. Thus the difference is only relative rather than absolute, making it impossible to use this criterion statigraphically unless a considerable roundness study has been made of a particular sand formation.

The difference in roundness was found to occur at the immediate contact between the inner beach and the outer dune so that a distance of a few feet

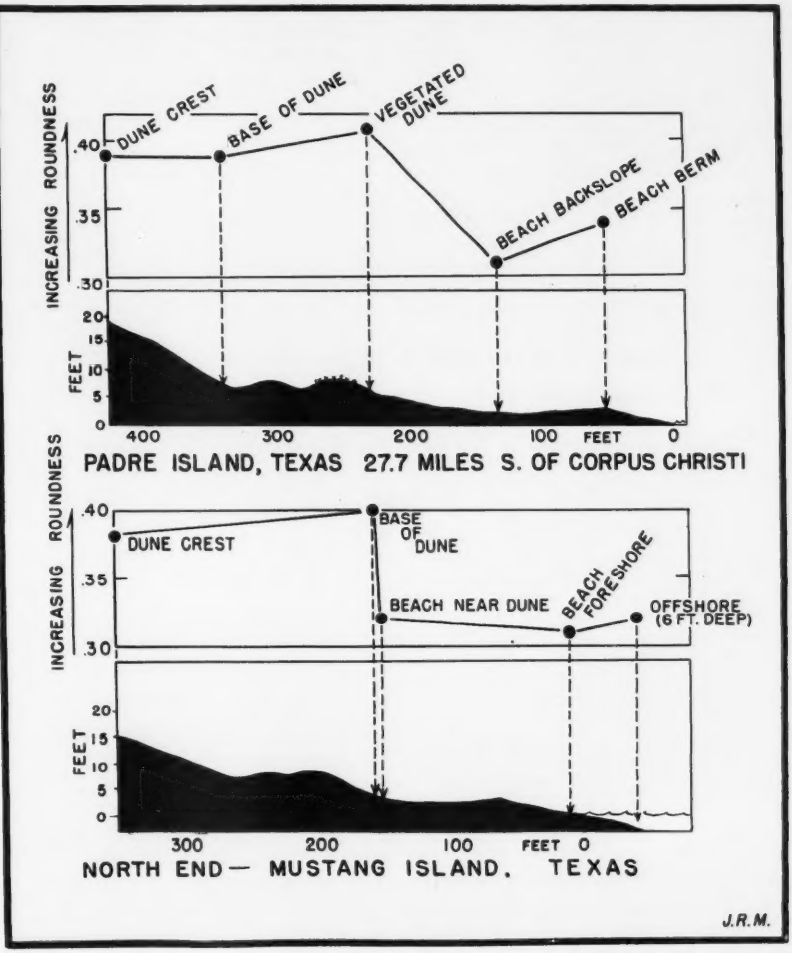

FIG. 4.—Variations of roundness along two beach-dune traverses. Note the sudden change in roundness at the beach-dune contact in the lower diagram.

makes a complete change in the roundness picture. This is shown in figure 4. In tracing the roundness away from the beach across an extensive series of dunes little change was found. Samples obtained during a hurricane tide, when the water covered a low dune on the inner beach of northern Padre Island, showed that the overrun dunes still had high roundness (fig. 5). However, the roundness here is lower than in the dune interior.

EXPLANATION OF DIFFERENCE IN ROUNDNESS

The preceding discussion shows that the roundness in the dunes is not a matter of abrasion or it would increase with distance from the beach and little or no contrast would be found at the dune beach contact. MacCarthy (1935), in working with adjacent beach and dune samples from the east coast, found that the dunes had a higher sphericity than the beaches and suggested as an explanation a selective sorting by the wind. Subsequently MacCarthy and Huddle (1938) were able to produce such a sorting in laboratory experiments. Krumbein (1942) suggests that roundness itself is not a factor in the selective sorting, but because of the correlation between sphericity and roundness a selective sorting according to sphericity results also in a roundness sorting.

Due to the rather extensive areas studied and the limited time available, sphericity determinations have not been made a part of this study. Consequently, it is not possible to draw conclusions as to whether sphericity or roundness or some combination of both is responsible for the suggested selective sorting. The results of the present study do, however, confirm the popular belief that dune sands are more rounded than the adjacent beach sands and this information could be put to use in stratigraphic studies.

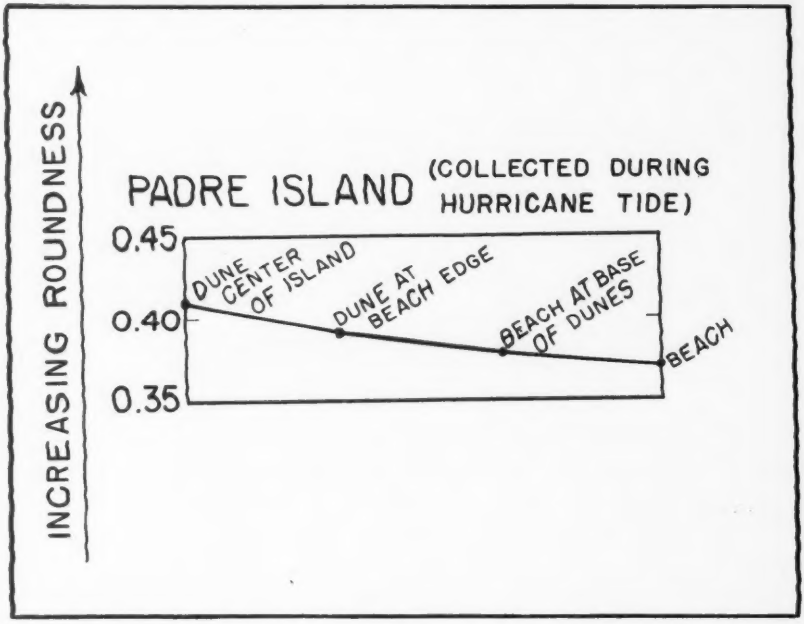

FIG. 5.—Showing a persistence of dune roundness values despite over-running of low coastal dunes by a hurricane tide. Note that the beach referred to here had been a dune prior to the hurricane.

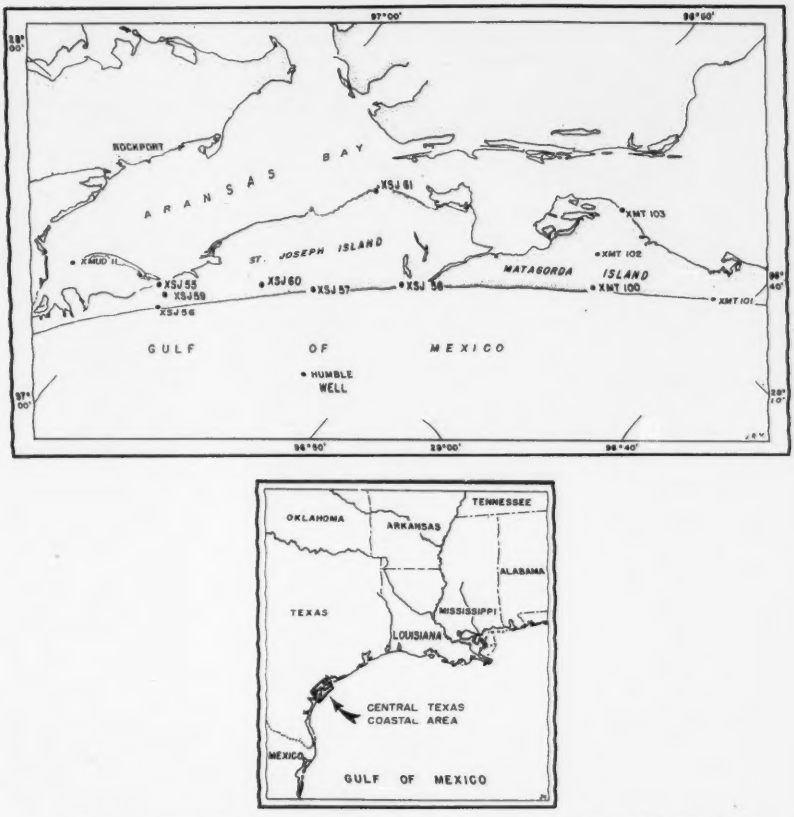

FIG. 6.—Location of borings in the central Texas coastal area from which roundness values were obtained.

ROUNDNESS IN SHALLOW BORINGS

Twelve borings were made on St. Joseph and Matagorda islands (fig. 6), going to an average depth of 50 feet (Shepard and Moore, 1955). Most of the material obtained in these borings was sand. Therefore, it became important to determine roundness in many of the samples to see if they might have been deposited under dune conditions. Of 26 samples studied, five showed distinct dune roundness and two others have a roundness of 0.34 which is more likely to be in the dune category than beach. At 14 feet below the beach on Matagorda Island a distinct dune roundness was discovered at a level which is about 12 feet below present sea level. On St. Joseph Island at 29 feet below the beach a roundness of 0.34 was found in two of the holes. In a boring on the inside of the dune ridge of St. Joseph Island a sample was obtained at 44 feet which had a roundness of 0.36 and is thus quite clearly in the dune category (fig. 7a). All of

these samples are of a type which could be explained as a dune deposit (Shepard and Moore, 1954).

A boring was made at Jaybird Point on the Aransas Bay side of St. Joseph Island, and one on an exposed tidal flat at the

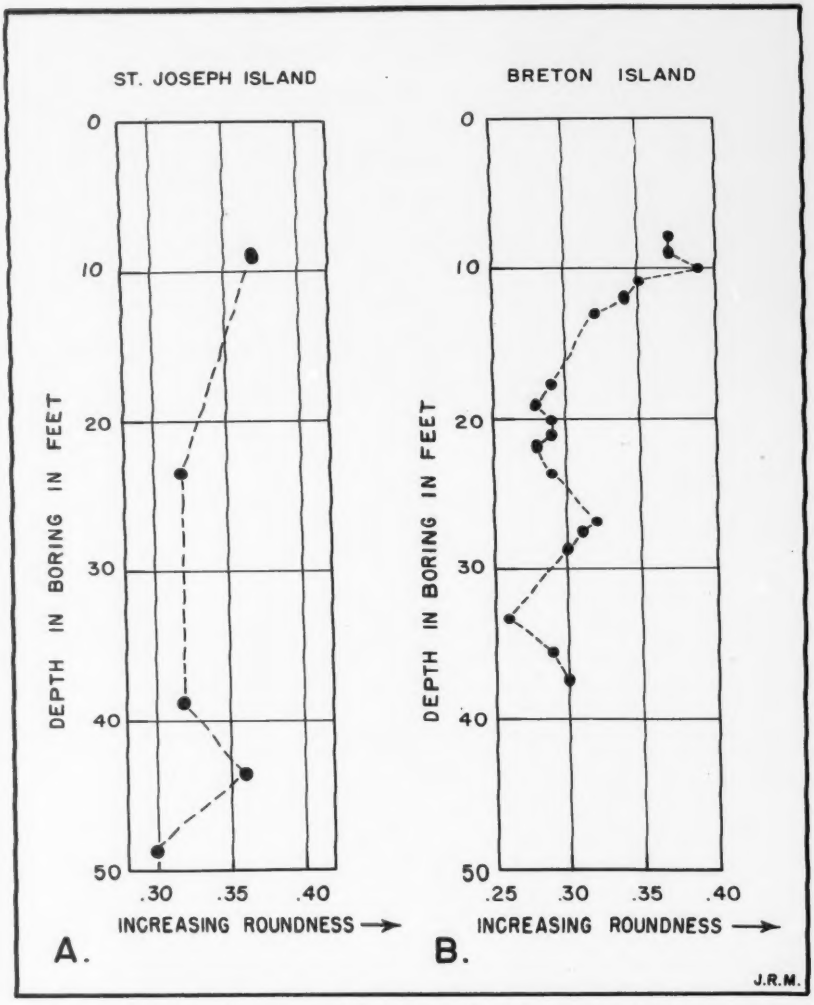

FIG. 7.—Plot of roundness values with depth in boring (A) on St. Joseph Island in the Central Texas coastal area, and (B) on Breton Island in the East Mississippi Delta area. Roundness values of surface sample greater than .33 are found to be dune sands.

FIG. 8.—Showing the vegetated ridges on Matagorda Island which are commonly referred to as "beach" ridges, but are shown to have a dune roundness value. Note that the "beach" ridges have been overrun by dunes in some areas. (Aerial mosaic courtesy of Tobin Aerial Surveys, Inc.)

tip end of Mud Island, an extension of St. Joseph Island into Aransas Bay. Cores from both borings contained deposits which differ from typical dune sand in having about 10 percent silt and clay, but these sands showed a roundness of 0.37 at a depth of 32 feet under Jaybird Point and of 0.39 and 0.40 at depths of 16 and 17 feet respectively under Mud Island. The material lacks the faunas typical of bay deposits (figure by Parker in Shepard and Moore, 1955, fig. 38) and it would appear that either this represents a dune sand into which a certain amount of silt and clay has been blown or that dune sands have been reworked by an overwash containing some muddy sediment.

In a boring made by Humble Oil and Refining Company at a locality three and one-half miles seaward of St. Joseph Island, a sample was obtained above the Pleistocene contact at a depth of 25 feet below the ocean bottom in which a roundness of 0.42 was obtained. This sample was from a series extending through a thickness of 60 feet, all apparently formed on a barrier island or in inlets crossing such an island (Shepard and Moore, 1955, p. 1569).

Roundness studies were also made on 12 samples from two borings in the east Mississippi Delta area extending to a depth of 33 feet below the surface of Breton Island. Two samples from a depth of approximately 12 feet showed a roundness value comparable to that of the present day dune sands of Breton Island. The remainder of the sand samples from the borings yielded roundness values comparable to the present beach sands of Breton Island (fig. 7b).

BEACH RIDGES OR DUNE RIDGES

Ridges like those shown in the accompanying aerial photograph (fig. 8) are usually referred to as "beach-ridges." It is assumed by most people that they have been built on a prograding shoreline where storms have built up the sand or gravel above the general sea level. Such ridges are discussed extensively by Johnson (1919, pp. 404–453). Examination of many coastal areas has shown that storm beaches made of cobbles are quite common, but, so far as the writers know, sand is not built up into land ridges by storm waves. On the other hand, a series of submerged bars and troughs are found along many coasts and some of these may be built up at least to high tide level. Long sand ridges inside beaches are also built by the wind. Sometimes these ridges are narrow and parallel to the shore and in other places they are less ridge-like and spread over a wide area.

In order to determine whether the so-called "beach-ridges" of Matagorda and St. Joseph islands along the Texas coast were the product of piling up of sand by the waves or whether they represent dune ridges, a series of samples was obtained. These samples extended from the surface to depths of as much as seven feet in the parallel ridges and a few were obtained in the swales or valleys between ridges. An average roundness of 0.37 has been determined for these samples. The values are plotted in figure 2 and it can be seen that all but one of the samples is clearly in the dune category and the one represents a point of overlap between a dune and beach. This seems to indicate that, at least in this area, the so-called "beach-ridges" should actually be called "dune-ridges." A possible reason for there being more than one ridge could be that the beach has made a series of progradations and a dune-ridge was formed inside the beach at each stand.

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———, 1935, Volume, shape, and roundness of quartz particles: Jour. Geology, v. 43, pp. 250–280.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 1, PP. 61–63
FIGS. 1–2, MARCH, 1956

A SIMPLE TURBIDIMETER

JOHN S. BRADLEY
Institute of Marine Science, The University of Texas, Port Aransas, Texas

ABSTRACT

A simple turbidimeter for measuring suspended solids in sea water for the range 0 to 1000 parts per million was made from a light meter, variable voltage transformer, and a light globe. The instrument may prove of value in other sedimentation studies.

INTRODUCTION

A method of determining the suspended solids in sea water for the range 0 to 1000 parts per million was needed for the study of sediment transport by tidal and drift currents. To meet this need a simple home-made instrument, utilizing a photographic light meter, a variable voltage transformer and a light globe was designed. This turbidimeter is described because of the availability of the components, the simplicity of design and use, and the wide range of conditions over which it may be calibrated.

The use of the transmission of light (or lack of it) to determine the amount of suspended material in water is far from new. Although the Secchi disc is used primarily to record absorption of light in pure sea water, it may also be used to determine the turbidity of the water. In the "standard candle" method of determining turbidity, the length of a column of water is measured as the candle approaches extinction. Richardson (1934, 1936) designed a recording photo-electric apparatus for delineating the size-frequency of clays. This instrument is available commercially (Krumbein & Pettijohn, 1938).

DESCRIPTION

A standard 100-watt, tungsten filament, frosted, light globe is connected to a variable voltage transformer so that the brightness will vary with the voltage. A glass container, containing the turbid water sample, is placed between the light globe and a light meter (fig. 1). The entire system is shielded from stray light. The light meter is brought to a standard reading (20 in this case) by adjusting the voltage. The voltage is read, compared to a calibration chart, and the parts per million of suspended material are read directly from the chart (fig. 2).

A standard laboratory model, 0–115 volt, "Powerstat" or "Variac" serves as voltage control. The wattage of the light globe may be varied to give on scale readings for various turbidities and for various sample holders. The light meter used was a Weston Master II Universal Exposure Meter, although any standard meter should suffice. A 32-ounce, wide mouth, sample jar ($3\frac{3}{8}$ inches inside diameter) was used both for collecting the sample and in the turbidimeter. The light globe was shielded in a tin can and the sample bottle was shielded in a mailing tube with friction cap. The light meter was clamped to the side of the mailing tube opposite the light source and shielded with tape.

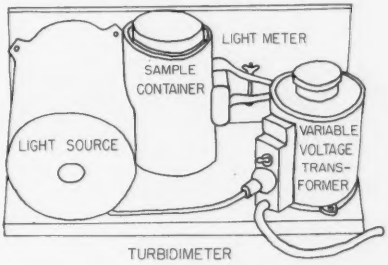

FIG. 1

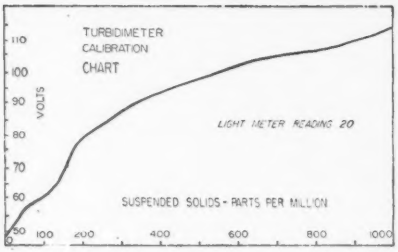

FIG. 2

DISCUSSION

In use it was found much easier to read voltage with the light meter reading held constant, than to read the light meter for a constant voltage. A change of voltage of one-quarter volt affects the light meter reading. For the prototype instrument, accuracies of 5 to 15 ppm from 0 to 400 ppm and 15 to 25 ppm from 400 to 1000 ppm were obtained by reading to the nearest volt. Greater accuracy is possible in any given range by varying the light globe, the sample jar (distance light travels through sample), and the standard light meter reading. Changes in line voltage were compensated for by periodically taking a reading on a standard sample. In measuring the turbidity of sea water samples, it was found that organic growth increased the turbidity over a period of time. It would, therefore, appear necessary to take readings within a day or two after sampling when the samples are not sterile.

To construct a calibration chart, a series of 10 standards between 0 and 1000 parts per million (by weight) were made up from distilled water and kaolin. The graphs of voltage vs. parts per million were made up for various constant light meter readings (table 1). A constant meter reading of 20 was chosen for the range of 0 to 1000 ppm because of the ease of reading and the convenient spread of voltages (48–114 volts). The instrument could just as easily be calibrated against standards by weight or volume; standards of silica, kaolin, or of the actual sediment to be studied; standards of distilled water, tap water, or filtered sea water; or standards of varying grain size sediments.

By increasing the light wattage or by decreasing the sample jar diameter the range of the instrument can be extended to at least 50 parts per thousand suspended material (approximately 50 grams suspended matter per liter). Calibration of the instrument against the pipette method would give a rapid, accurate method for routine fine-grained sediment analyses. The advantage of the present instrument over the hydrometer method is not pronounced in the range above 10 parts per thousand, but from 0 to 10 parts per thousand the turbidimeter is much more accurate. Thus, by adequate dilution of the sample, a more accurate analysis could be made easier than with the hydrometer. This turbidimeter may also be used instead of the slower sedimentation or sewage cone.

The advantages of the turbidimeter stem from its inherent simplicity. There

TABLE 1.—*Turbidimeter calibration*

Distilled Water and Kaolin Standard, parts per million	Voltage with light meter reading 5	Voltage with light meter reading 10	Voltage with light meter reading 20
1000	76	95	114
800	72	88	106
600	70	84	102
400	65	77	93
200	57	68	79
100	44	50	60
50	42	48	57
0	37	43	48
Filtered sea water 0 ppm	37	43	48
Blank (empty sample bottle)	40	46	54

are no constant voltage regulators, no optical quartz tubes, no constant volume pumps, no electronically balanced circuits. By varying the three components, the degree of accuracy and the range of analysis may be adjusted widely. The instument may be made to use any standard sample container so that transfer and mixing of samples is unnecessary. The instrument is, of course, susceptible to refinement and modification, such as light filters, narrow band, constant wave length light source, standard area and length sample containers, lens systems, and a variety of photo-multiplier tubes. However, for most sedimentary analyses, the simple instrument appears to give adequate accuracy.

CONCLUSION

The turbidimeter has been found to serve its original purpose of determining suspended sediment in sea water with both accuracy and ease. This instrument and its possible modifications, because of its ease of use, may be of value as an auxiliary instrument in routine sedimentary analyses now performed by pipette, hydrometer, and settling tube methods. Further, the instrument may be used to extend the range of these methods.

REFERENCES

KRUMBEIN, W. C. AND PETTIJOHN, F. J., 1938, Manual of sedimentary petrography. Appleton-Century, New York, 549 pp.

RICHARDSON, E. G., 1934, An optical method for mechanical analysis of soils, etc.: Jour. Agric. Sci., v. 24, pp. 457–468.

RICHARDSON, E. G., 1936, A photo-electric apparatus for delineating the size frequency curve of clays or dusts: Jour. Scientific Instruments, v. 13, pp. 229–233.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 1, PP. 64–66
FIGS. 1–2, MARCH, 1956

NOTES

A MANUAL PISTON CORING DEVICE FOR USE IN SHALLOW WATER[1]

ROBERT N. GINSBURG[2] AND R. MICHAEL LLOYD[2]
Marine Laboratory, University of Miami

INTRODUCTION

A recent paper by Hanna (1954) in this Journal described the construction and operation of a hand coring rig for use in shallow water. The authors have constructed a similar type of device to obtain cores from mud flats and water less than five feet dep. The authors' design differs from Hanna's in that a piston is used to prevent compaction of the sediment caused by friction between the sediment and the tube wall. This modification was found to be essential to obtain a full core in sticky fine-grained sediments. When a simple open tube was forced into the sediment there was as much as 50% compaction of the core.

The use of a piston to counteract friction between the core and core tube was introduced by Kullenberg (1947) for deep sea work.

DESCRIPTION

The coring device consists of a piston, a bipod frame, two-inch o.d. plastic tubing, and a pair of hand slips. The piston which fits inside the plastic tubing is held at the surface of the sediment by a cable attached to the bipod frame (fig. 1). The hand slips grip the plastic tubing for both forcing it into the sediment and pulling it out.

Frame

The bipod frame as shown in figure 1 is made from two pieces of $1\frac{3}{4}$″ dowel each ten feet long which are joined together at one end with a strap hinge. The free ends of the dowels are fitted with hinged "feet" to provide bearing surface when used in soft sediment. A pulley is attached at the apex of the frame to take the piston cable. A cable clamp fitted with a wing nut for securing the piston cable is bolted to one leg at a convenient height above the foot.

Cable and Piston

Two types of pistons have been used with success. The simplest and least expensive is made from a No. 10 rubber stopper (fig. 2C) and a short $\frac{1}{4}$″ eye bolt. The stopper is cut down so that it will

FIG. 1.—Piston coring rig assembled and in operating position.

[1] Contribution No. 150 from The Marine Laboratory, University of Miami. This device was designed and constructed as part of American Petroleum Institute Project #51. The authors gratefully acknowledge the technical assistance of Joel Kupperberg.

[2] Present address: Shell Oil Co., 4029 Ponce de Leon Boulevard, Coral Gables, Florida.

fit the inside of the tubing snugly. A second stopper may be mounted above the first as a guide.

A more permanent piston (fig. 2B) can be fashioned from brass stock. A leather washer is fitted to one end and an eye bolt brazed on the other.

For convenience the piston cable is divided into two parts. A three-foot length of $\frac{1}{8}$" cable is permanently attached to the piston and has a spring clip fastened to the free end. Another length of cable, 10 to 12 feet in length, which runs through the frame pulley, is fitted with a thimble to take the spring clip. In a later model heavy sash chain was substituted for cable and was found easier to handle.

Hand Slips

A pair of hand slips is fashioned from pipe stock (fig. 2A). A three-inch length of two-inch i.d. iron pipe is split in half lengthwise. Teeth are raised on the interior surface of the pipe sections with a narrow cold chisel. A short piece of female joint is welded onto each section, and pieces of one-inch pipe screwed into the joints to serve as handles. The sections are hinged together well above the two-inch pipe to prevent binding when the slips are opened.

Cable Holder and Reducer

A brass cable holder (fig. 2D) when placed over the tube and tightened down on the cable is helpful in preventing the piston from slipping under vacuum when the core tube is removed from the sediment.

A number of two-inch sections of $1\frac{1}{4}$" o.d. steel tubing are sharpened on one edge (fig. 2E). These are force-fitted into the ends of the plastic tubes to serve as cutting edges and reducers.

OPERATION

The bipod is set up with a leg spread of two to three feet to form a rigid frame. The two parts of the piston cable are joined and the piston forced down to the bottom of the coring tube with an eight-

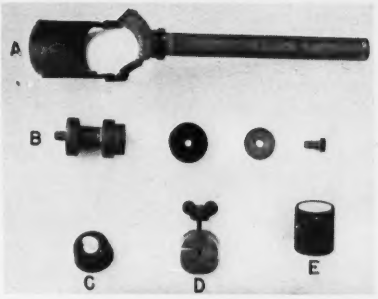

FIG. 2.—Details of coring rig. A—slips (one-pipe handle removed); B—brass piston with leather washer and retaining screw; C—rubber stopper piston; D—cable holder; E—reducer.

foot length of $\frac{3}{8}$" pipe or reinforcing rod where it is stopped by the reducer. The slips are then slid over the bottom end of the coring tube with the hinges toward the top. With the coring tube standing vertically and resting on the sediment surface, slack is taken up on the cable and the cable firmly fixed with the cable clamp on the frame.

The slips are raised half way up the tube. Downward pressure on the slips causes them to grip the tube and force it into the sediment. Successive bites are taken on the tube until the desired depth is reached. The cable holder is then attached to the piston cable at the top of the coring tube and the piston cable unhooked at the spring clip. The slips are lifted off the tube, turned so the hinges are pointing down, and slipped back over the tube. By successive bites the tube is lifted from the sediment. A cork is placed in the bottom and the tube sawed with a hack saw just above the top of the sediment and corked at the top. The core may be extruded or the plastic tube split for examination of the core.

PERFORMANCE

Single cores up to seven feet long have been obtained with this device. The sediment was 30 to 90 percent silt and clay-sized with occasional zones of shells

and fragments and layers of turtle-grass peat. The device did not function well in sediments which were predominantly sand-sized.

Cores up to ten feet in length were obtained by a modification of the technique described above. After a seven-foot core has been taken the piston is pushed to the bottom of a 12-foot tube and the tube inserted in the hole made by the first core. During the insertion, the piston is held at the bottom of the tube with a rod. When the tube reaches the bottom of the seven-foot hole, as indicated by measurement, the piston cable is made fast and the coring begun at the minus seven-foot level, as described above.

The use of reducers is not required in many cases, but because they cut down internal wall friction and cut fibrous plant debris, they are recommended. The outside of the core is usually smeared, but no internal distortion of laminations and peat-sediment contacts have been observed.

Core catchers have not been found necessary thus far, but with other sediments they may be needed.

REFERENCES

HANNA, MARCUS A., 1954, A simple coring tube for soft sediments: Jour. Sedimentary Petrology, v. 24, pp. 263–269.

KULLENBERG, B., 1947, The piston core sampler: Svenska Hydrobiolo. Komm. Skrifter, S. 3, v. 1.

MINERAL COMPOSITION OF THE YAZOO CLAY BY X-RAY DIFFRACTION METHODS

ALAN D. BUCK
P. O. Drawer 2131, Jackson, Mississippi

The approximate composition of the minus 2-micron fraction of the Yazoo clay was determined using the method of Johns, Grim, and Bradley (1954). The Yazoo is an Eocene clay which is the upper formation of the Jackson group in Central Mississippi. It has most recently been described by Monroe (1954). The sample was obtained in an unweathered condition from a shot hole a few miles southwest of Jackson, Mississippi. The exact location is just east of the section corner of sec. 32, 33, T.6 N., and 4, 5, T.5 N., R. 1. W. at an elevation of 300 feet, near the top of the Yazoo clay (Monroe, 1954, plate 2).

The sample was prepared by separating the minus 2-micron portion from the remainder by sedimentation in distilled water. A water suspension of the fine material was allowed to settle onto a glass slide which was then removed from the water. This clay film was examined air-dry and after saturation with c.p. glycerol. The equipment used was a General Electric XRD-3 with diffractometer, employing Cu radiation at 49 kvp and 16 ma, filtered through 0.0007-in. Ni foil; target angle of 4°, scanning speeds of 2°, 0.2° (2θ) per minute, 1° beam slit, MR Soller slit, 0.1° detector slit.

The indicated composition of the sample was:

Clay Minerals	*Percent*
Kaolinite group	45
Montmorillonoid	30
Illite	15
Non-Clay Minerals	*Percent*
Quartz, carbonate, feldspar	10
Total	100

Monroe (1954) states that Bay (1935, pp. 40–42) reported bentonite (?) in the Yazoo clay near Jackson and commented "The Yazoo clay . . . is characterized by two zones that are probably bentonitic—one in the very base . . . , the other near the top."

The sample reported herein was obtained by Bryant Mather and the suggestion that it be examined was made by Katharine Mather, both of whom have assisted in the preparation of this note.

REFERENCES

Bay, H. X., 1935, A preliminary investigation of the bleaching clays of Mississippi: Mississippi Geol. Survey, Bull. 29.

Johns, W. D., R. E. Grim, and W. F. Bradley, 1954, Quantitative estimation of clay minerals by diffraction methods: Jour. Sedimentary Petrology v. 24, pp. 242–251.

Monroe, W. H., 1954, "Geology of the Jackson area, Mississippi." U. S. Geol. Survey Bull. 986, pp. 57–59.

68

PLASTIC SPRAY IN LABORATORY AND FIELD

JAMES E. CONKIN
Union Producing Co., Beeville, Texas

Acrylic plastic sprayed from an aerosol bomb is useful in preparing slides and sections and in strengthening and protecting specimens in the laboratory or field. Some notes on these uses of plastic spray are presented here.

The brand of plastic spray used is Krylon Acrylic Spray No. 1303, made by Krylon, Inc., Philadelphia, Pa. This plastic is colorless, nontoxic, quick-drying, and hard and smooth when dry. It is convenient and inexpensive.

With thin sections, the plastic may be used instead of the traditional cover glass with balsam. The plastic is applied by holding the aerosol bomb about a foot away from the ground section and spraying the section with two or more thin coats. The drying time for two coats is about five minutes. Excess plastic can be removed easily with xylol. Sections prepared with the plastic are clear and free from bubbles. These thin sections can be photographed or used in place of negatives in a photographic enlarger.

If desired, a cover glass may be used with the plastic, but the drying time is then several hours; nevertheless, the section can be examined without damage while the plastic is setting.

With polished sections, the plastic may be used instead of painting with shellac or Alvar. The sprayed surface is smooth, and it is hard enough to permit easy handling and storing of the sections.

The plastic spray may be used in the laboratory or field instead of shellac or Alvar to strengthen specimens and/or to protect them from chemical reactions (as when fossils are replaced by marcasite).

Plastic spray may also be used in preparing slides of material from cuttings, crushed cores, or surface samples by placing such material upon glass or paper slides and then fixing it with the plastic.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 1, P. 69, MARCH, 1956

REVIEW

Petrographic Mineralogy, by Ernest E. Wahlstrom. 1955. Pp. vii+408; 5½×8½ in., John Wiley & Sons, Inc., New York, Price $7.50.

This book is essentially a revision of *Igneous Minerals and Rocks* which appeared in 1947. The general scope, however, is changed, and attention is given only to laboratory studies of minerals and rocks. The book consists of petrographic techniques (largely microscopic), mineral descriptions and determinative tables, and outline descriptions of rocks. Emphasis is placed on the use of thin sections and, unfortunately, the equally important method of oil immersion study is scarcely more than mentioned. A review of the technique and problems encountered in this widely used microscopic method should deserve at least a few pages of text. Without this experience, involving perhaps the most fundamental optical properties of minerals, the student comes to depend upon "cook-book" mineral descriptions based on properties determined from thin sections, many of which are unreliable, obsolete, or erroneous.

This is not intended as a slur upon the section dealing with optical properties of minerals, because this section appears to be the best in the book. Compared with the earlier edition, this section is much more accurate and complete. It brings out better the relation between chemistry and optics of minerals. The many chemical-optical graphs are a commendable feature.

The numerous photomicrographs are, in general, good; but many of them are not of sufficiently good quality to deserve the space they take. A number of others could have been masked to cover half the area without sacrificing quality.

The line drawings showing optical orientation in different minerals are particularly instructive, but the reviewer fails to see the value of including the indicatrix in all of these figures. Diagrams showing positions of X, Y, Z, and the optic axes relative to crystal axes and faces are not only adequate but simpler, and can be clearly seen if reduced to one-half. This would enable many more figures to be included to good advantage. A set of six such figures to illustrate the plagioclase series for example would have been a worthwhile inclusion.

Much material dealing with classification, detailed description, and geological occurrence of igneous rocks in the earlier edition, has been eliminated from this book. It seems strange, however, that the author chooses to discuss the norm calculation, but fails to include a set of calculation rules, merely refers to Niggli's scheme, and totally ignores the valuable system of Barth.

A new chapter provides a simplified and clear account of the employment of the universal stage, a valuable petrographic tool which has been sadly neglected in sedimentary rock studies. Here the reader will find the essentials for mastering the simpler and commonly used universal stage methods, involving both stereographic and equal-area projection.

Two new chapters on the composition, properties, and classification of sedimentary and metamorphic rocks help to render the book more useful particularly to readers of this journal.

Those finding Wahlstrom's earlier work *Igneous Minerals and Rocks* of value will be particularly interested in this more recent revision. They will find it more useful, more authentic, and more up-to-date.

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University of Illinois
Urbana, Illinois

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 1, PP. 70–100
MARCH, 1956

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

PROGRAM FOR S.E.P.M., CHICAGO MEETING (Conrad Hilton Hotel)

Robert R. Shrock, Technical Program Chairman

SUMMARY OF PROGRAM

SUNDAY, APRIL 22

Registration	ALL DAY
S.E.P.M. Council	2 P.M.

MONDAY, APRIL 23

Registration and Committee Meetings, Grand Ballroom	9 A.M.
Research Committee Symposium: Directional Properties of Sedimentary Rocks, Grand Ballroom	1:45 P.M.
Special Panel Session: Discussion of Topics Covered by Symposium, Follows Immediately	
Meeting of Research Committee	5:00 P.M.

TUESDAY, APRIL 24

Joint Session with A.A.P.G.; Addresses, Honors, and Awards, Grand Ballroom	9:00 A.M.
General Paleontology and Stratigraphy, Waldorf Room	1:45 P.M.
Annual Business Meeting, Waldorf Room	4:30 P.M.

WEDNESDAY, APRIL 25

Symposium on Paleoecology, Waldorf Room	9:00 A.M.
Mineralogy and Sedimentary Petrology, Waldorf Room	1:45 P.M.
Annual Dinner Dance	EVENING

THURSDAY, APRIL 26

Mineralogy and Sedimentary Petrology, Waldorf Room	9:00 A.M.
General Paleontology and Stratigraphy, Waldorf Room	1:45 P.M.
Meeting of New S.E.P.M. Officers	4:00 P.M.

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
PROGRAM FOR 30TH ANNUAL MEETING

MONDAY, APRIL 23 — 1:45 P.M.

Grand Ballroom, Conrad Hilton Hotel

RESEARCH COMMITTEE SYMPOSIUM: DIRECTIONAL PROPERTIES OF SEDIMENTARY ROCKS

Part I, Presentation of Papers

1. INTRODUCTION, Raymond Siever, Illinois State Geological Survey, Urbana, Illinois
2. FLUME EXPERIMENTS ON THE PRODUCTION OF STRATIFICATION AND CROSS-STRATIFICATION, Edwin D. McKee, U. S. Geological Survey, Washington, D. C.
3. SAND-GRAIN ORIENTATION AND GEOLOGICAL APPLICATION, Gene A. Rusnak, Scripps Institution of Oceanography, La Jolla, California
4. GRAIN ORIENTATION STUDIES OF RECENT SANDS, Joseph R. Curray, Scripps Institution of Oceanography, La Jolla, California
5. DIRECTIONAL PROPERTIES OF SOME CALIFORNIA SANDSTONES, L C. Bonham, California Research Company, La Habra, California
6. ORIENTED PHENOMENA PRODUCED BY SEDIMENTATION FROM TURBIDITY CURRENTS AND IN SUBAQUEOUS SLOPE DEPOSITS, John E. Sanders, Yale University, New Haven, Connecticut
7. TRACING TURBIDITY CURRENT DEPOSITS DOWN THE SLOPE OF AN ALPINE BASIN, Albert Carozzi, University of Illinois, Urbana

Part II, Panel Discussion

Discussion of each paper will be deferred until all papers have been presented.

TUESDAY, APRIL 24 9:00 A.M.

Grand Ballroom, Conrad Hilton Hotel

JOINT SESSION WITH AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS AND SOCIETY OF EXPLORATION GEOPHYSICISTS

Addresses, Honors, and Awards

Presiding for S.E.P.M.: J. Marvin Weller, University of Chicago

IN DEFENSE OF OUTDOOR GEOLOGY
Francis J. Pettijohn, President, Society of Economic Paleontologists and Mineralogists

PRESENTATION OF S.E.P.M. AWARDS
Raymond Siever, Illinois State Geological Survey
Best Paper in 1954 in Journal of Paleontology
Recipient: Donald Parkinson, Birmingham, England
Best Paper in 1954 in Journal of Sedimentary Petrology
Recipients: H. N. Fisk, E. McFarlan, Jr., C. R. Kolb, and L. J. Wilbert, Jr. (Deceased); Houston, Texas, Houston, Texas, and Vicksburg, Mississippi

S.E.P.M. HONORARY MEMBERSHIP
J. Marvin Weller
Recipient: Raymond C. Moore, University of Kansas

TUESDAY, APRIL 24 1:45 P.M.

Waldorf Room, Conrad Hilton Hotel

GENERAL PALEONTOLOGY AND STRATIGRAPHY

1. ECOLOGICAL INTERPRETATION OF THE PLIOCENE AND PLEISTOCENE STRATIGRAPHY IN THE GREAT PLAINS REGION, John C. Frye & A. Byron Leonard, Illinois State Geological Survey, Urbana, Illinois; University of Kansas, Lawrence, Kansas
2. PROBLEM OF SCIENTIFIC NOMENCLATURE APPLICABLE TO FRAGMENTARY FOSSILS, Raymond C. Moore & P. C. Sylvester-Bradley, University of Kansas, Lawrence, Kansas; University of Sheffield, Sheffield, England
3. SIGNIFICANCE OF LIVING FORAMINIFERAL POPULATIONS ALONG THE CENTRAL TEXAS COAST, Fred B. Phleger, Scripps Institution of Oceanography, La Jolla, California
4. PALEOECOLOGY OF THE FLORIDA MIOCENE, Harbans S. Puri & Robert O. Vernon, Florida Geological Survey, Tallahassee, Florida
5. RECENT AND ANCIENT PENETRANTS, Maxim K. Elias, University of Nebraska, Lincoln, Nebraska
6. SEDIMENTARY REFLECTIONS OF THE DEPOSITIONAL ENVIRONMENT IN A COASTAL LAGOON, Harris B. Stewart, Jr., Scripps Institution of Oceanography, La Jolla, California
7. MARINE ECOLOGY AS AN AID IN THE TEACHING OF INVERTEBRATE PALEONTOLOGY AND STRATIGRAPHY, William H. Mathews, III, Lamar State College of Technology, Beaumont, Texas

WEDNESDAY, APRIL 25 9:00 A.M.

Waldorf Room

SYMPOSIUM: PALEOECOLOGY

1. INTRODUCTORY REMARKS, Robert R. Shrock, Massachusetts Institute of Technology, Cambridge, Massachusetts
2. PLAN OF SYMPOSIUM, Harry S. Ladd, U. S. Geological Survey, Washington, D. C.
3. MARINE LEVEL-BOTTOM ANIMAL COMMUNITIES OF RECENT SEAS, Gunnar Thorson, Copenhagen Zoological Museum, Copenhagen, Denmark
4. CONDITIONS OF LIFE IN THE SEA, Joel W. Hedgpeth, Scripps Institution of Oceanography, La Jolla, California
5. PALEOECOLOGICAL EVIDENCE FURNISHED BY FOSSILS, Harry S. Ladd, U. S. Geological Survey, Washington, D. C.
6. PALEOECOLOGICAL EVIDENCE FROM SEDIMENTS, Bernhard Kummel, Harvard University, Cambridge, Massachusetts
7. DIATOMS AS PALEOECOLOGICAL INDICATORS, Kenneth E. Lohman, U. S. Geological Survey, Washington, D. C.
8. NEW TECHNIQUES IN PALEOECOLOGY, Philip H. Abelson, Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.

WEDNESDAY, APRIL 25 — 1:45 P.M.

Waldorf Room

MINERALOGY AND SEDIMENTARY PETROLOGY

1. UNIFORMITARIANISM IS A DANGEROUS DOCTRINE, Paul D. Krynine, The Pennsylvania State University, University Park, Pennsylvania
2. TERTIARY REEF LIMESTONES FROM SOUTHERN LOUISIANA AND GUAM, McLain J. Forman & Seymour O. Schlanger, c/o Gordon Atwater, consulting geologist, New Orleans, Louisiana; U. S. Geological Survey, Washington, D. C.
3. REVISIONS IN THE MINERALOGY OF THE FUNAFUTI DRILL CORES AND THEIR BEARING ON THE PHYSIOCHEMISTRY OF DOLOMITE, Robert F. Schmalz, Army Chemical Center, Maryland
4. HEAVY-MINERAL ASSEMBLAGES OF THE CORAL-REEF LIMESTONES AT THE BASE OF THE TRICHINOPOLY CRETACEOUS (CENOMANIAN TO DANIAN), SOUTH INDIA, G. Gundu Rao, The Pennsylvania State University, University Park, Pennsylvania
5. PETROGRAPHY AND GENESIS OF THE OGALLALA "ALGAL LIMESTONE" IN KANSAS AND ADJACENT STATES, Ada Swineford, John C. Frye, & A. Byron Leonard, State Geological Survey of Kansas, Lawrence, Kansas; Illinois State Geological Survey, Urbana, Illinois; University of Kansas, Lawrence, Kansas
6. SHELF-EDGE, CALCAREOUS PROMINENCES IN THE NORTHEASTERN GULF OF MEXICO, John C. Ludwick & William R. Walton, Gulf Research and Development Company, Houston, Texas
7. SILURIAN REEFS OF THE NORTHERN EDGE OF THE EASTERN INTERIOR BASIN, John B. Sangree, Jr., Northwestern University, Evanston, Illinois
8. TRANSITIONAL PERMO-PENNSYLVANIAN SEDIMENTS OF THE ROWE-MORA BASIN, NEW MEXICO, Raymond Sidwell & G. Frederick Warn, Texas Technological College, Lubbock, Texas

THURSDAY, APRIL 26 — 9:00 A.M.

Waldorf Room

MINERALOGY AND SEDIMENTARY PETROLOGY

1. ALICE IN GRAYWACKELAND, Paul D. Krynine, The Pennsylvania State University, University Park, Pennsylvania
2. RELATION OF PETROLOGY AND STRUCTURE TO PRODUCTIVITY IN A STRATIGRAPHIC TRAP, LINDEMANN (McMILLAN SAND) OIL FIELD, RUNNELS COUNTY, TEXAS, Morton K. Blaustein, Midland, Texas
3. PERMEABILITY LOSS FROM SWELLING OF MATRIX CLAYS IN SUB-GRAYWACKES, G. Harvey Hamilton & George R. Downs, Union Oil Company of California, Denver, Colorado; Consulting Geologist, Denver, Colorado
4. DIFFERENTIAL COMPACTION OF PENNSYLVANIAN SEDIMENTS IN RELATION TO SAND-SHALE RATIOS, JEFFERSON COUNTY, ILLINOIS, Joseph C. Mueller & Harold R. Wanless, Continental Oil Company, Oklahoma City, Oklahoma; University of Illinois, Urbana, Illinois
5. CLAY-MINERAL COMPOSITION OF RECENT SEDIMENTS FROM THE MISSISSIPPI RIVER DELTA, W. D. Johns, Jr., & R. E. Grim, University of Illinois, Urbana, Illinois
6. ENVIRONMENTAL CONDITIONS AFFECTING THE DEPOSITION OF BEACH SANDS BETWEEN VIRGINIA AND FLORIDA, Suzanne F. Bershad & John K. Duncan, Division of Oceanography, U. S. Navy Hydrographic Office, Washington, D. C.
7. MIDDLE PALEOZOIC TECTONIC HISTORY OF NORTH-CENTRAL AND NORTHWESTERN UTAH, James E. Brooks, Southern Methodist University, Dallas, Texas
8. TRIASSIC IN THE EASTERN GREAT BASIN, David L. Clark & William Lee Stokes, University of Iowa, Iowa City, Iowa; University of Utah, Salt Lake City, Utah

THURSDAY, APRIL 26 — 1:45 P.M.

Waldorf Room

GENERAL PALEONTOLOGY AND STRATIGRAPHY

1. THE IDENTIFICATION OF OSTRACODE GENERA AND SPECIES IN THIN SECTIONS, Stuart A. Levinson, Humble Oil & Refining Company, Houston, Texas
2. A FAUNULE OF UNUSUAL NONMARINE OSTRACODA FROM THE PLIOCENE OF IDAHO, Daniel J. Jones & Norman R. Anderson, University of Utah, Salt Lake City, Utah
3. CONODONTS FROM THE TYPE CHESTER, ILLINOIS, Carl B. Rexroad, Texas Technological College, Lubbock, Texas

4. UPPER DEVONIAN SUBSTAGES AND THEIR WORLD-WIDE CORRELATION ON THE BASIS OF CONODONTS, Klaus J. Müller, State University of Iowa, Iowa City, Iowa
5. SPECIFIC VARIATIONS AMONG ARENACEOUS SILURIAN FORAMINIFERA FROM ILLINOIS, Howard Schwalb & Charles Collinson, Illinois State Geological Survey, Urbana, Illinois
6. *ACANTHOCLADIA GUADALUPENSIS* GIRTY, A POSSIBLE ALGAL-BRYOZOAN SYMBIOT, J. Keith Rigby, Brigham Young University, Provo, Utah
7. DENDRASTER: A PROBLEM IN ECHINOID TAXONOMY, D. M. Raup, Harvard University, Cambridge, Massachusetts

ANNOUNCEMENTS

FIFTH NATIONAL CLAY CONFERENCE

The Fifth National Clay Conference will be held at the University of Illinois, Urbana, Ill., Oct. 8, 9, and 10, 1956. The conference is sponsored annually by the Clay Minerals Committee of the National Academy of Sciences—National Research Council, under the chairmanship of Prof. R. E. Grim of the University of Illinois.

Contributed papers on subjects related to clay mineralogy or technology will be welcome. Titles for inclusion in the program must be received by May 1, and short informative abstracts will be required by June 15. Titles and abstracts may be sent to Dr. W. F. Bradley, Illinois Geological Survey, Urbana, Illinois.

More detailed announcements will be distributed about April 1.

ANNUAL MEETING OF THE PERMIAN BASIN SECTION OF THE S. E. P. M.

The annual meeting of the Permian Basin Section of the Society of Economic Paleontologists and Mineralogists is scheduled for May 11 and 12 in Fort Worth, Texas, at which time the new officers will assume their duties. The new officers are:

President: Hugh N. Frenzel, 1118 Mogford St., Midland, Texas

First Vice-President: W. Frank Dameron, B. B. M. Drilling Co., Midland, Texas

Second Vice-President: Frank Counselman, 849 Leggett Dr., Abilene, Texas

Secretary: Tom Schneider, Texas Pacific Coal and Oil Co., Midland, Texas

Treasurer: Edward A. Vogler, Shell Oil Co., Midland, Texas

MEMBERS OF THE SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

Members	900
*Associates	280
‖Correspondents	5
†Honorary Members	3
	1188

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Osborne, James G., Jr.
Petersen, Richard G.
Reinhart, Philip W.
Rezak, Richard
Rothrock, David Paul
Russell, Orville R.
Russell, R. Dana
Shaw, Alan B.
Shelton, John W.
Teichert, Curt
Tourtelot, Harry A.
Durango—
Elias, Gregory K.
Hallstein, William W.
Knight, Raymond L.
Lauth, Robert E.
Sanders, John Warren
Golden—
Cathcart, James B.
Hayes, John R.
Johnson, J. Harlan
LeRoy, Leslie W.
Mateer, Warren D.
Grand Junction—
Bowen, Charles H.
Cadigan, Robert A.
Robeck, Raymond C.
Travis, Richard
Weir, Gordon W.
Williams, George A.
Lafayette—
Moore, Fred E.

CONNECTICUT

Darien—
Jones, Verner
Hartford—
St. Jean, Joseph, Jr.
Middletown—
Lehmann, Elroy Paul
New Haven—
Dunbar, Carl O.
Sanders, John E.

DISTRICT OF COLUMBIA

Washington—
Bassler, R. S.
Bates, Charles C.
Berninghausen, William H.
Bershad, Suzanne F.
Boardman, Richard S.
Castigliola, Julius
Chappars, Michael S.
Cohee, George V.
Cooper, Chalmer L.
Duncan, John Kenneth
Edsall, Thomas D., III
Finley, Emmett A.
Gardner, Julia
Gordon, MacKenzie, Jr.
Hack, John T.
Henbest, Lloyd G.
Herbert, Paul, Jr.
Lang, Walter B.
Loeblich, Alfred R., Jr.
Manger, G. E.
Neuman, Robert B.
Rubey, William W.
Schmidt, Ruth A. M.
Sohl, Norman F.
Sohn, I. G.
Taylor, Dwight W.
Williams, James Steele
Wrather, W. E.

FLORIDA

Coral Gables—
Olsson, Axel A.
Crystal Beach—
Wisner, William A.
Orlando—
Twenhofel, W. H.
Sarasota—
Knight, J. Brookes
Tallahassee—
Caldwell, Eleanor T.
Lund, Ernest H.
Puri, Harbans S.
Tanner, William F.
Toulmin, Layman D.
Yon, James W., Jr.

GEORGIA

Atlanta—
Allen, Arthur T., Jr.
Savannah—
Spraul, Gary L.

IDAHO

Moscow—
Grimm, Kenneth E.

ILLINOIS

Carbondale—
DuBar, Jules R.
Cherry—
Kraye, Robert Frank
Chicago—
Fisenberg, Marvin
Emiliani, Cesare
Kahn, J. Steven
Krinsley, David H.
Nitecki, Matthew H.
Otto, George H.
Sangree, John B., Jr.
Thomas, Norman L.
Weller, J. Marvin
Effingham—
Bristol, Hubert M.
Elsah—
Robertson, Percival
Evanston—
Dapples, Edward C.
Krumbein, W. C.
Sloss, Laurence L.
Mattoon—
Henton, John M., Jr.
Mt. Vernon—
Brehm, Clarence E.

Olney—
Hamblin, Ralph H.
Nuttall, Brandon
Oswego—
Bokman, John
Paxton—
Peterson, John E.
Salem—
Allison, James M.
Hockman, James N.
Urbana—
Brophy, John Allen
Collinson, Charles W.
Frye, John C.
Grim, Ralph E.
Hough, Jack L.
Johnson, Robert B.
Rhodes, Frank H. T.
Ross, Charles A.
Schwalb, Howard Ray
Scott, Harold W.
Siever, Raymond
Swann, David H.
Wanless, Harold R.
Wilson, George M.

INDIANA

Bloomington—
Galloway, Jesse J.
Gray, Henry H.
McGregor, Duncan
Murray, Haydn H.
Pinsak, Arthur P.
Notre Dame—
Gutschick, Raymond C.
Terre Haute—
Baird, Donald W.

IOWA

Ames—
Hussey, Keith M.
Brandon—
Stainbrook, Merrill A.
Iowa City—
Furnish, William M.
Miller, A. K.
Tester, Allen C.
Trowbridge, A. C.

KANSAS

Independence—
Studt, Charles W.
Kansas City—
Hawkins, Harold H.
Lawrence—
Dellwig, Louis Field
Fay, Robert O.
Ireland, Hubert A.
King, Ralph H.
Laukel, Quinn C.
McManus, Dean A.
Merriam, Daniel Francis
Moore, Raymond C.
Swineford, Ada
Thompson, M. L.
Youngquist, Walter L.

Mission—
Bunch, Rosella L.
Wichita—
Batchelor, Jo Wolter
Carmody, Robert A.
Douglass, Harry Marvin
Koester, Edward A.
Rector, Glasco W.
Tasch, Paul
Walters, Robert F.
Zajic, William E.

KENTUCKY

Hopkinsville—
Nosow, Edmund

LOUISIANA

Baton Rouge—
Brockhouse, Robert B.
Camacho, Enrique
Cheetham, Alan H.
Delaney, Patrick J.
Durham, Clarence O., Jr.
Howe, Henry V.
Murray, Grover E.
Lake Charles—
Chatham, E. Walter, Jr.
Latta, Lee Allen
Morrow, A. Lyndon
Rudick, Walter James
Tabbert, R. L.
Taylor, Jack A.
Tipsword, Howard Lee
Warren, Albert D.
Lafayette—
Anderson, Irvin J.
Etter, John
Gimbrede, Louis de A.
Gooch, D. D.
Paine, William R.
Varvaro, Gasper Gus
Wiley, Richard A.
New Orleans—
Akers, Wilburn H.
Bane, M. Ray
Braunstein, Jules
Cameron, Donald K., Jr.
Clark, Robey H.
Ferguson, H. C.
Forman, McLain, Jr.
Morgan, Aylmer Lee, III
Philpott, Thomas H.
Slama, Don C.
Tonti, Edmond C.
Ruston—
Higgs, William R.
Shreveport—
Brown, Dwight M., Jr.
Craver, Frank S., Jr.
Danehy, Edward A.
Hazzard, Roy T.
Sprouse, Donald W.

MAINE

Orono—
Trefethen, Joseph M.

MARYLAND

Baltimore—
Fairley, William M.
Pettijohn, Francis J.
Beltsville—
Carroll, Dorothy
Hathaway, John S.
Bethesda—
Stephenson, Lloyd W.
Chevy Chase—
Ladd, Harry S.
Edgewood—
Bebout, Don G.
Hyattsville—
Reeside, John B., Jr.
Schultz, Hildreth N.
Kensington—
Dante, John Henry
Queenstown—
White, Maynard P.
Rockville—
McIntyre, John B.
Suitland—
Burns, Robert E.
Kaufman, Oscar

MASSACHUSETTS

Amherst—
Johansson, Warren Irving
Wilson, Leonard R.
Bedford—
Dott, Robert H., Jr.
Boston—
Hecht, Richard J.
Cambridge—
Barghoorn, Elso
Kummel, Bernhard
Mencher, Ely
Moore, James R., III
Shrock, Robert R.
Stetson, Henry C.
Natick—
Hubert, John F.
Northampton—
Shaub, Benjamin M.
Williamstown—
Ramsdell, Robert C.
Woods Hole—
Athearn, William D.

MICHIGAN

Ann Arbor—
Briggs, Louis I.
Kellum, Lewis B.
Landes, Kenneth K.
Detroit—
Sanford, John T.
East Lansing—
Kelly, William A.

MINNESOTA

Minneapolis—
Cornell, James R.
Goldich, Samuel S.
Holt, Olin R.

Sloan, Robert Evan
Swain, Fred M.
Northfield—
Stewart, Duncan

MISSISSIPPI

Hattiesburg—
West, Jesse W.
Jackson—
Adams, Emmett R.
Applin, Esther R.
Brown, Charles E.
Johnson, Wendell B.
Karges, Harold E.
Kirby, Louie C.
Mather, Katharine
Mellen, Frederic F.
Phillips, Scott, H.
Rainwater, E. H.
Scurlock, Clarence R.
Taylor, Waller E.
Tench, Robert Norman
Laurel—
Hughes, Urban B.
State College—
Smith, William H.
University—
Hughes, R. J., Jr.
Shaver, Robert H.
Vicksburg—
Van Lopik, Jack R.

MISSOURI

Columbia—
Bradley, Daniel A.
Keller, W. D.
Peck, Raymond E.
Unklesbay, Athel G.
Ferguson—
Echols, Dorothy Jung
Kansas City—
Greene, Frank C.
Rolla—
Frizzell, Don L.
St. Louis—
Brice, James Coble
Hinchey, Norman S.

MONTANA

Billings—
Beekly, Emerson K.
Darrow, George F.
Doroshenko, Jerry
Munyan, Arthur C.
Richards, Paul W.
Shepard, Herbert Warren
Sonnenberg, Frank P.
Stainforth, Robert M.
Great Falls—
Gribi, Edward A., Jr.

NEBRASKA

Lincoln—
Elias, Maxim K.
Lugn, Alvin L.
Reed, Eugene C.
Whelan, Thomas J., Jr.

NEW HAMPSHIRE

N. Conway—
Hattin, Donald E.
Portsmouth—
Sage, Nathaniel M., Jr.

NEW JERSEY

Glen Ridge—
Emery, John Rathbone
Hopewell—
Pierson, J. R., Jr.
New Brunswick—
Fox, Steven K., Jr.
Martens, James H. C.
Princeton—
Hess, Harry H.
Howell, B. F.
Van Houten, Franklyn B.
S. Orange—
Nine, Ogden W., Jr.

NEW MEXICO

Albuquerque—
Bourn, Oscar B.
Hayes, Philip T.
Thorp, Eldon M.
Wengerd, Sherman A.
Carlsbad—
Pratt, Wallace E.
Farmington—
Petty, John K.
Raymond, Paul C.
Roswell—
Ehlmann, Arthur J.
Fickman, Philip
McNulty, Charles L., Jr.
Meyer, Richard F.
Newsom, Y. B.
Shepard, R. H.
Sweeney, H. N.
Winkler, Hans
Socorro—
Pitrat, Charles W.

NEW YORK

Brooklyn—
Wang, Kia-Kang
Buffalo—
Hibbard, Raymond R.
Nadeau, Betty Kellett
Ithaca—
Palmer, Katherine V. W.
Mamaroneck—
Dresser, Hugh
New York—
Cruse, John S., Jr.
Dietz, Robert S.
Ellis, Brooks F.
Fairbridge, R. W.
Flagler, C. W.
Imbrie, John
Jaekel, Julie Ann
James, John W.
Kaufmann, Godfrey F.
Kay, Marshall
King, Robert Evans
Knebel, George Moses
Messina, Angelina R.
Newell, Norman D.
Page, Lou Williams
Schaffel, Simon
Terry, Jack S.
Thralls, Warren H.
Pittsford—
Alling, Harold L.
Poughkeepsie—
Johnsen, John H.
Warthin, A. S., Jr.
Rochester—
Sutton, Robert G.
Syracuse—
Apfel, Earl T.
Troy—
Beers, Roland F.
Lowman, Shepard W.
Williston—
Cochran, John A.

NORTH CAROLINA

Chapel Hill—
Ingram, Roy L.

NORTH DAKOTA

Bismarck—
Harris, Steven H.
Tudor, Mathew S.
Fargo—
Pye, Willard D.
Grand Forks—
Holland, Frank D., Jr.

OHIO

Athens—
Sturgeon, Myron T.
Cincinnati—
Abbott, Ralph E.
Caster, Kenneth E.
Columbus—
Leutz, Willard P.
Levinson, Alfred A.
Schopf, James M.
Spieker, Edmund M.
Summerson, Charles H.
Sweet, Walter C.
Weiss, Malcolm P.
Dayton—
Chilingar, George V.
Coryell, Horace N.
Oxford—
Martin, Wayne D.

OKLAHOMA

Ardmore—
Johnson, William R.
Neustadt, Walter, Jr.
Speer, John Hill
Tomlinson, Charles W.
Westheimer, Jerome Max
Wilson, Ruth B.
Bartlesville—
Hicks, I. Curtis
Passega, Renato
Strimple, H. L.
Weeks, Warren B.

Chickasha—
Bryan, J. Victor
Enid—
Baker, Vernon R.
Clifton, R. L.
Muir, J. Lawrence
Muskogee—
Wallace, Maurice H
Newkirk—
Schoonover, Jack G.
Norman—
Branson, Carl C.
Culp, Eugene F.
Curtis, Doris Malkin
Curtis, Neville, M., Jr.
Decker, Charles E.
Frederickson, Edward A.
Harris, Reginald W.
Huffman, George G.
Jordan, Louise
Lucas, Elmer Lawrence
Moore, Carl A.
Oklahoma City—
Adent, William A.
Blythe, Jack Gordon
Eisner, Stephen M.
Heyman, Louis
Isbell, Grover Jim
Jacobsen, Lynn
Kate, Frederick H.
McGee, Dean A.
Pasquella, George G.
Pollard, Robert T.
Reiter, Frederick H.
Tubb, George G.
Turk, Lon B.
Shawnee—
Phillips, David Lee
Stillwater—
Schreiber, Joseph F., Jr.
Tulsa—
Bennison, Allan P.
Bramlette, W. A.
Branson, Herberta Van Pelt
Busch, Daniel A.
Campbell, Charles V.
Connolly, Frank T.
Contreras, Carlos E.
Daetwyler, Calvin C.
Denison, A. Rodger
Ellsworth, Elmer W.
Enlows, Harold E.
Goldstein, August, Jr.
Grigsby, R. B.
Harlton, Bruce H.
Hawkins, Glenn D.
Hoffmeister, William S.
Hopkins, M. E.
Kauffman, James S.
Kjellesvig-Waering, E. N.
Kornfeld, Joseph A.
Levorsen, A. I.
Martin, James L., Jr.
Miller, Paul M.
Porterfield, Robert R.
Reeves, James E.
Rhoades, Sam J., Jr.
Ryniker, Charles
Sarmiento-Soto, Roberto
Scruton, Philip C.
Snider, James W.
Steele, Grant
Stephenson, Morton B.
Stone, Solon W.
Vernon, Roger C.
Wagner, Carl D.

OREGON

Corvallis—
Bostwick, David A.
Eugene—
Baldwin, Ewart M.
Bressler, Calder T.
Portland—
Stewart, Roscoe E.

PENNSYLVANIA

Bethlehem—
Willard, Bradford
Lancaster—
Moss, John Hall
Shepps, Vincent C.
Lewisburg—
Powers, Maurice C.
Philadelphia—
Weeks, H. J.
Pittsburgh—
Cox, Ben B.
Fettke, Charles R.
Hedberg, Hollis D.
Lattman, Laurence H.
Sass, Louis Carl
Sutton, A. H.
Tator, Benjamin A.
University Park—
Griffiths, J. C.
Krynine, Paul D.
Stanley, Edward A.
Swartz, Frank M.

RHODE ISLAND

Kingston—
Garrison, Louis Eldred
McMaster, Robert L.

SOUTH DAKOTA

Rapid City—
Tullis, Edward L.
Vermillion—
Agnew, Allen F.
Stevenson, Robert Evans

TENNESSEE

Memphis—
Marcher, Melvin V.

TEXAS

Abilene—
Conselman, Frank B.
Fountain, H. C.
Hada, John L.
Hayward, Charles W.
Morrison, Robert E.
Samuell, John Howard
Schenck, Walter L.
Amarillo—
Britt, Harry M., Jr.
Craig, Thomas C.
Tarver, Jack H.
Austin—
Adkins, W. S.
Amsbury, David L.
Barnes, Virgil E.
Bell, W. Charles
Damon, H. Gordon
Eartle, D. Hoye
Ellison, Samuel P., Jr.
Flawn, Peter T.
Folk, Robert L.
Grant, Richard E.
Gurel, Mehmet
Horton, Claude W.
Lonsdale, John T.
Mankin, Charles
Morey, Philip S.
Myers, Donald A.
Pittman, James S., Jr.
Twining, John T.
Whitney, F. L.
Young, Keith P.
Beaumont—
Beck, Frank Ralph
Eveland, Harmon E.
Matthews, William H., III
Strachn, Clarence H., Jr.
Beeville—
Conkin, James Elvin
Bellaire—
Caldwell, Barbara S.
Chun, Harold A.
Holliday, Samuel
Kilgore, John E.
Masson, Peter H.
Setzer, Francis M.
Breckenridge—
Pitzer, Phillip M.
Cedar Valley—
O'Hara, James F., Jr.
Coleman—
Rothrock, Howard E.
College Station—
Koenig, Karl J.
Lynch, Shirley A.
Smith, Fred E.
Corpus Christi—
Abrahamson, E. C.
Bannahan, Annabelle
Campbell, A. Richard
Clarkson, Louise Freeman
Cook, Theodore D.
Giltner, Robert F.
Higgins, Maurice J.
Holcomb, Charles W.
Krause, Erwin K.
Lohse, E. Alan
Middour, E. S.
Owens, Frith Cravens
Dallas—
Albritton, Claude C., Jr
Alexander, C. I.
Allen, John L.
Aschenbrenner, B. C.
Billingsley, Harold Ray

Bradfield, Herbert H.
Brooks, James E.
Clark, John W.
DeGolyer, E.
Doering, John A.
Dunlap, John B., Jr.
Frost, Jack
Fuqua, Irene Sribny
Green, Cecil H.
Grubbs, David M.
Haertlein, James A.
Hamilton, I. B.
Karcher, John C.
MacNaughton, Lewis W.
McCluer, Robert D.
McCommons, William E.
McLeod, Angus
Meyer, Willis G.
Montgomery, James H.
Moreman, Walter L.
Perkins, Bob F.
Richards, Arthur
Robertson, Herbert C., Jr.
Robinson, Van D.
Sellin, H. A.
Stehr, Raymond A.
Thompson, Sam, III
Thompson, S. A.
Tripp, R. Maurice
Wiggins, Peter N.
Williams, Harry F.
Williams, James R.
Wilson, Starkey
Woodard, Robert L.
Zimmerman, Donald A.

El Paso—
Baldwin, Don C.
Nelson, Lloyd A.

Fort Worth—
Cooley, Douglas R.
Donoghue, David
Harges, Marvin E.
Hendricks, Leo
King, William Edward
McBride, Mary Wood
McEachin, Wright D.
McKay, Alexander E.
Moore, Walter L.
Schweers, Richard H.
Stewart, Wendell J.

Galveston—
Artusy, Raymond L.

Gorman—
Brogdon, Dewey Robert

Houston—
Albers, Charles C.
Alexander, W. H., Jr.
Baker, William A., Jr.
Barker, R. Wright
Beach, Paul R.
Bell, Olin G.
Bernard, Hugh A.
Bright, Anna Lou
Brixey, Austin D., Jr.
Bush, James
Carstens, Fred D.
Colle, Jack O.
Consiglio, Louis A.
Cotton, Edgar A.
Cram, Ira H.
Croneis, Carey
Crouch, Robert W.
Denham, Richard L.
Deussen, Alexander
Dillingham, Hervie, Jr.
Ellis, Albert D., Jr.
Fan, Paul H.
Fisk, Harold N.
Garrett, J. B., Jr.
Goodrich, Paul K.
Griffin, George M.
Halbouty, M. T.
Halsted, Morris E.
Hanna, Marcus A.
Hornberger, Joseph, Jr.
Hsu, K. Jinghwa
Ikins, William C.
Jeffords, Russell M.
Kellough, Gene Ross
LeBlanc, Rufus J.
Levinson, Stuart A.
Lohman, Clarence, Jr.
Lozo, Frank E.
Ludwick, John C.
Major, C. Fred, Jr.
Malicoat, Arthur F.
Martyn, Phil F.
McFarlan, Edward, Jr.
Monaghan, Patrick H.
Montgomery, J. C.
Moody, Clarence L.
Morrison, T. E.
Munsey, Gordon C., Jr.
Nanz, Robert H., Jr.
Nelson, Paul Hugh
Nygren, Walter Eric
O'Malley, F. Ward
Overton, Charles K.
Parker, William G.
Parks, James M., Jr.
Payne, Thomas G.
Petrusek, Benjamin J.
Phillips, Henry H.
Pyeatt, Lloyd M.
Quigley, Claude M., Jr.
Reiter, W. A.
Reynolds, E. Julius
Rittenhouse, Gordon
Ritts, L. Chase, Jr.
Rolshausen, F. W.
Rotan, Cleone M.
Sawin, Horace J.
Scrafford, John Bruce
Selig, A. L.
Smith, Denver J.
Smith, Fred L., Jr.
Smith, William Thomas
Speed, Carlton D., Jr.
Stenzel, H. B.
Stevenson, Frank V.
Stubbs, Sidney A.
Stuckey, Charles W., Jr.
Sutherland, Patrick K.
Tatum, Emmett P.
Treadwell, Robert C.
Trimm, Warren M.
Walk, Hugh G.
Walter, Joe C., Jr.
Walton, William R.
West, Glen D.
Westmoreland, Frank S.
Whipple, G. Leslie
Wilson, James Lee
Wimberley, C. Stanley
Woods, Raymond D.

Karnes City—
Kirsch, M. Ivo, Jr.

La Pryor—
Grant, Drane Fones

Lubbock—
Arper, William B., Jr.
Brand, John Paul
Mattox, Richard B.
Rexroad, Carl B.
Sidwell, Raymond
Wade, F. Alton

McAllen—
Lalicker, Cecil G.
Means, John A.

Midland—
Adams, John Emery
Clarkson, Wm. G., Jr.
Crotty, Burns M.
Davis, Billy Glen
Ewbank, Norman Ware, Jr.
Frenzel, Hugh N.
Gibson, George R.
Hajek, Charles F.
Hitt, Jack L.
Hollingsworth, R. V.
Hull, J. P. D., Jr.
Kerr, S. Duff, Jr.
Keyser, Joseph E.
Leibrock, R. M.
Lovejoy, Bill P.
Luckett, Joseph W., Jr.
Madden, Lloyd Willis
Mills, Lloyd C.
Muery, Warren E.
Oppel, Richard Edward
Perusek, Cyril J.
Rindsig, Julia K.
Rodgers, Jack P.
Sanderson, George A., Jr.
Schmitt, George T.
Scobey, Ellis H.
Skinner, John W.
Spencer, Maria
Stead, Frederick L.
Taylor, Howard Dean
Toomey, Donald F.
Vogler, Edward A.
Warren, Walter C.
Wilde, Garner Lee
Williams, Harold L.

Odessa—
van West, F.

Port Aransas—
Bradley, John S.

Richardson—
Scull, Berton J.
Weart, Richard C.

San Angelo—
Gregory, Joseph N.

Murphy, Daniel J.
Rhodes, Mary Louise
San Antonio—
Fritz, Joe F.
Grasso, Volker C.
Magaw, Mary Catherine
Owen, Edgar W.
Petty, Dabney E.
Rogers, James K.
Sandidge, John R.
Siemer, William J.
Still, J. T.
Tartamella, Natale J.
Theessen, E. J.
Seagoville—
Waters, James A.
Seguin—
Kniker, Hedwig T.
Seymour—
Kemp, Augusta Hasslock
Spring—
Aves, Charles A.
Tyler—
Eaton, Robert Wesley
Hamberg, Lawrence R.
Hurlbut, Elvin M., Jr.
Nichols, Paul H.
Peters, Theodore C.
Raasch, Albert C., Jr.
Rees, Barbara Leigh
Uvalde—
Welder, Frank A.
Waco—
Turner, James, A., Jr.
Wichita Falls—
Davis, Charles E.
Dennis, Lyman C.
Drake, Robert T.
Richards, David T.
Tripp, Ethel Davis

UTAH

Moab—
Norman, Robert R.
Salt Lake City—
Barkell, Clifford A.
Darrow, Richard L.
Hill, John Davis
Jones, Daniel J.
Linville, Andrew F., Jr.
Lyon, Craig A.
Osmond, John C., Jr.
Peterson, James A.
Richards, H. Glenn
Schnurr, Paul Eugene
Stokes, William Lee
Turner, Francis E.
Weiss, Hans

VIRGINIA

Alexandria—
Goldman, Marcus I.
McLean, James D., Jr.
Charlottesville—
Young, Robert S.
Falls Church—
Palmer, Allison R.
Ft. Lee—
Price, Charles E., Jr.
Lexington—
Stow, Marcellus H.

WASHINGTON

Pullman—
Scott, W. Frank
Seattle—
Coombs, Howard A.
Fulmer, Charles V.
Gould, Howard R.
Mallory, V. Standish
Wheeler, Harry E.
Tacoma—
McMillin, Frederick A.

WEST VIRGINIA

Clarksburg—
Bayles, Robert E.
Morgantown—
Heald, Milton T.

WISCONSIN

Green Bay—
Riggs, Elliott A.
La Crosse—
Gehrig, John Leonard
Madison—
Cline, Lewis M.
Tyler, Stanley A.
Zeller, Edward J.

WYOMING

Basin—
Lease, Leslie W.
Casper—
Byrne, Frank E.
DeLong, Jack M.
Heacock, Robert L.
Little, Curtis J.
Mills, Norman K.
Peterson, Marvin L.
Storm, Paul V.
Swirczynski, Richard P.
Worland—
Hanson, Alvin M.

OUTSIDE THE UNITED STATES

ALASKA

College—
Freeman, Val LeRoy

ALBERTA

Calgary—
Andrichuk, John M.
Atkinson, Eric
Burgers, Willem
Chakravorty, Sailendra
Chamney, T. Potter
Chilton, Mertie Ann
Crombie, Gordon P.
DeWit, Rein
Erickson, Robert H.
Fong, George
Goodman, A. J.
Hilgers, C. L. L.
Hunt, C. Warren
MacKay, Ian H.
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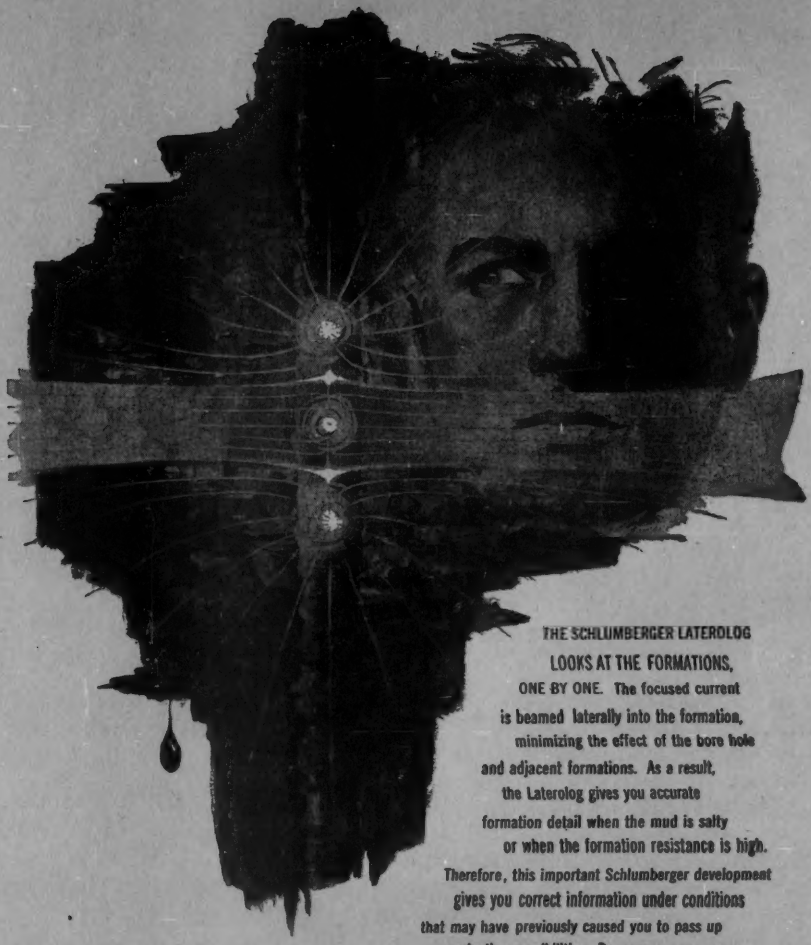

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